DEVELOPMENT OF A SYSTEMATIC APPROACH FOR UNCERTAINTY ASSESSMENT IN SCHEDULING MULTIPLE REPETITIVE CONSTRUCTION PROCESSES BY USING FUZZY SET THEORY

By

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This document is dedicated to all the women that devoted their life to the advancement of science

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DEVELOPMENT OF A SYSTEMATIC APPROACH FOR UNCERTAINTY ASSESSMENT IN SCHEDULING MULTIPLE REPETITIVE CONSTRUCTION PROCESSES BY USING FUZZY SET THEORY

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A growing portion of the U.S. Interstate highway system needs major rehabilitation and/or reconstruction. Many highway segments are located in or near major urban corridors serving high traffic volumes throughout the day and performing as critical links for local and through traffic. Shutting down a highway segment for rehabilitation and/or reconstruction work for extended periods of time will have as consequences considerable inconvenience and increased delays for road users, major community disruption, and significant economic loss. Applications of procedures to improve planning, scheduling, and control of highway construction and maintenance projects can reduce these inconveniences.

In order to achieve significant reductions in highway construction project times a broader, systematic approach to the problem is proposed.

Planning and scheduling of transportation construction projects is facilitated using the linear scheduling method (LSM) because of its visual and intuitive capabilities. One

of the main problems with LSM is that to date there is no formal method developed that could allow LSM to determine uncertainties in time completion.

In engineering, uncertainties can be attributed mainly to ambiguity, likelihood approximations and inconsistency. Several formal techniques for managing the different types of uncertainty have been developed but there has not been any consensus on the appropriateness of such techniques so far. It seems that there is no best theory of uncertainty and therefore the choice of the most appropriate technique depends upon the specific problem.

In response to these problems the fuzzy set theory is utilized to propose an efficient and systematic procedure for uncertainty assessment. The assessment procedure proposed is a heuristic tool that can process linguistic terms as used by experts allowing the quantification of expert knowledge in estimating and assessing uncertainty in scheduling repetitive construction projects.

CHAPTER 1
INTRODUCTION AND PROBLEM STATEMENT

1.1 Overview

The construction industry is one of the largest industries in the United States, constituting approximately ten percent of the United States' Gross National Product (Barrie, Paulson, 1992). As the construction engineering industry enters the twenty first century, construction engineering professionals are seeking to implement advanced technologies and develop improved project management practices.

A growing portion of the USA Interstate highway system needs major rehabilitation and/or reconstruction. Many highway segments are located in or near major urban corridors serving high traffic volumes throughout the day and performing as critical links for local and through traffic. Shutting down a highway segment for rehabilitation and/or reconstruction work for extended periods of time will have as consequences considerable inconvenience and increased delays for road users, major community disruption, and significant economic loss.

1.2 Problem Statement

Applications of procedures to improve planning, scheduling, and control of highway construction and maintenance projects can provide many benefits. Improved organization of the construction process usually reduces overall cost, increases construction safety, and shortens the project duration.

For new highway construction, a shorter duration increases public safety by allowing a needed highway to open earlier. For highway rehabilitation and reconstruction projects, benefits of shorter construction duration include reduced traffic delay and associated costs, fewer collisions and injuries associated with construction-related accidents, and lower capital costs for maintaining traffic that are associated with highway construction projects.

In order to achieve significant reductions in highway construction project times, a broader, more comprehensive approach to the problem is needed than looking for marginal improvements in existing techniques. Re-conceptualization of the problem during the planning phase, for example, might lead to alternative approaches to construction that could yield greater benefits in terms of reduced delay and disruption than could be achieved through typical approaches to minimizing contractor lane occupancy. Although project time reductions can be achieved in each of the project activities, the primary benefits will be realized during construction.

Despite the fact that at present the bar chart and the critical path method (CPM) scheduling techniques are most widely used for construction projects, a continued growing awareness of the fact that the traditional network is not the best tool for the planning of linear projects, and the shortcomings of bar charts in today's complex world has led to a resurgence of interest in linear scheduling method (LSM) to assist in planning these particular projects. One of the main limitations of LSM is the lack of a formal method developed to date that could allow LSM to determine uncertainties in time completion.

Construction projects are characterized by a unique and extremely complex nature which makes them highly sensitive to both internal and external factors. These factors inherently incorporate uncertainties into the project significantly affecting the outcome of the project In order to measure control and evaluate the performances of the construction projects, the construction schedule is a useful tool

Most schedules are developed in a deterministic manner by assuming that the activity durations are a single most likely numerical value known with some certainty In order to address uncertainty in construction projects the Program Evaluation and Review Technique (PERT) was developed in which each activity has a statistical distribution defined that represents its possible duration in the light of the uncertainty in the project The most often used distributions for the activity durations are the beta and triangular distributions, and their values are usually based on expert opinion taking into consideration the perceived risks associated with the expected project conditions

1.3 Research Objectives

1.3.1 General Comments

The overall goal of this research was to study the scheduling techniques used specifically for multiple repetitive construction projects, with special attention to the uncertainty factors inserted into these techniques. The research also involved developing a systematic approach for uncertainty assessment in scheduling repetitive construction projects This broad effort can be broken down into the following research objectives

1.3.2 Breakdown of the Research Objectives

1.3.2.1 Objective 1

The initial objective of this research was to identify and analyze all available information on the subject of scheduling multiple repetitive construction projects in order to produce a thorough review of the published literature and available documentation as well as existing software developed in the same area

1.3.2.2 Objective 2

After surveying several scheduling methodologies and thoroughly examining their suitability for scheduling repetitive construction projects, the next objective was to identify and analyze the problems encountered by previous researchers One of the main limitations identified was related to uncertainty assessment in the scheduling process. These limitations created the reasons behind the future development of the research

1.3.2.3 Objective 3

A fundamental objective of this research was the use of the most proper uncertainty theory such as the fuzzy set theory, to assess and implement the effects of different uncertain factors into the scheduling process. This experimentation was combined with the information collected from Objective 2 to evaluate the effectiveness of the new approach to overcome the inappropriateness of other methods.

1.3.2.4 Objective 4

Having developed a procedure with the ability to consider the effect of different types of uncertainties in scheduling repetitive construction projects the final objective was to develop a systematic approach to generate valuable information to be used in scheduling for different situations and different types of repetitive projects, and the elaboration of recommendations on the future use of this procedure

1.4 Research Methodology

1.4.1 General Comments

Part of this dissertation is based on research project conducted for the Florida Department of Transportation (FDOT). As such, most of the data and information collected and analyzed typically relate to FDOT highway construction operations

Although this research effort concentrated on FDOT documentation, any organization can utilize this basic approach in its generic form by simply using relevant specific data.

1.4.2 Breakdown of the Research Methodology Phases

1.4.2.1 Phase 1

An extensive literature search was performed through a large variety of state-of-the-art databases in the attempt to reveal the most up-to-date literature written and research done on the subject of scheduling in general and also on the subject of scheduling multiple repetitive construction processes in particular

The literature review had several outcomes

- The most commonly scheduling methods used in construction industry and the software supporting them were reviewed
- The scheduling methods most suitable and recommended by researchers and experts to be used for the particular case of repetitive construction projects were identified and studied
- The degree of usage of the recommended scheduling methods in repetitive construction projects was determined and analyzed

The first phase uncovered the fact that in the real-world of scheduling construction projects, the driving force of using a certain scheduling method is mainly the software availability, and not the efficiency or suitability of the method to a particular type of project This topic is detailed in Chapter 2

1.4.2.2 Phase 2

Since the selected area of focus was the scheduling of multiple repetitive construction projects a review of the basic principles and elements of the most popular and recommended methods of scheduling these particular types of projects was conducted In this phase numerous research papers were reviewed in order to examine the capabilities and drawbacks of these methods. Findings of this phase of the research are presented in Chapter 3

1.4.2.3 Phase 3

The next phase was to conduct a thorough analysis of the main types of uncertainties that affect construction processes generally. The uncertainty factors that affect the construction, the duration, and finally the scheduling of multiple repetitive construction projects were identified. This analysis was correlated with a review of the most popular methods used to characterize, evaluate and quantify uncertainty that led to the selection of the most appropriate method for assessing uncertainties that are not statistical in nature. The study continued by quantifying of the effect of different possible variables on project duration for the particular case of transportation construction projects. The results of these analyses are presented in Chapter 4

1.4.2.4 Phase 4

Conclusions drawn from the previous phases led to the determination that the best method to apply in assessing uncertainty in scheduling multiple repetitive construction processes is the fuzzy set theory. In this phase the mathematical principles and the computational methods of fuzzy sets of numbers were identified. The application of fuzzy set theory in uncertainty assessment during scheduling of typical project networks was presented. Once the fuzzy set theory was selected, as well as the computational tool to implement it, a fuzzy inference model was used in order to develop an uncertainty assessment procedure. A fuzzy scheduling algorithm tailored to the characteristics of the linear scheduling method was also proposed. The findings of this phase are presented in Chapter 5

1.4.2.5 Phase 5

The new uncertainty assessment procedure was validated by implementing it into a selected repetitive construction project. The validation process is presented in Chapter 6

1.4.2.6 Phase 6

Results from the entire research effort encompassing Phase 1 through Phase 6 were analyzed and conclusions and recommendations for future research are included in Chapter 7

CHAPTER 2
LITERATURE REVIEW

2.1 Project Scheduling Methods

2.1.1 Bar Chart

At present two scheduling techniques are being most used for construction projects the bar chart and the critical path method (CPM)

One of the most widely used methods of project scheduling is the bar chart. The bar chart graphically shows the activities versus time as shown in Figure 2-1 (Abeyasinghe Greenwood, Johansen, 2001). Normally time is on the horizontal axis and the activities are listed vertically, usually in the general sequence in which they will be performed

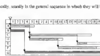

Figure 2-1 Gantt chart with time constraints

The major advantage of a bar chart is its simplicity and ease of understanding. The major disadvantage of a bar chart is that the interrelationships of the activities are not shown. One other significant shortcoming of a bar chart is that it usually lacks detail.

Activities are defined in broad categories with little or no breakdown by station, by span, and so on. Because of these shortcomings, it is difficult to identify delays or problems, to change sequence in response to problems, and to accurately measure progress during the execution of a broadly defined activity (Trauner, 1992). Further, in the case of linear activities, there is no convenient method of indicating known variations in the rate of progress (Johnston 1981)

2.1.2 Critical Path Method (CPM)

Critical path method (CPM) is one of the most common scheduling methods used in the construction industry (Mathla, Abraham, 1998) CPM is used to some degree by 92% of the ENR Top 400 contractors (Tavakoli, Riachi 1990)

CPM schedules are a graphical representation of the activities, their sequence and their interrelationships. Normally, this is called a network diagram The actual CPM then calculates the critical path, or the path of activities which if delayed will delay the overall completion of the project (Figure 2-2) The paths of activities that are not critical have discreet amounts of float or slack time that allow the manager to recognize how much slippage can be tolerated before affecting project progress.

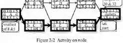

Figure 2-2 Activity on node

CPM networks are best used on projects that are comprised of distinct activities, and where the dependencies among those activities are complex and can be clearly defined However not all the projects are discreet in nature Rather, the activities progress continuously over the length of the project as in the case of transportation projects.

Highways construction involves activities such as clearing, grubbing, grading subbase construction, base course construction reinforcement placement, paving and shoulder construction Each of these activities as well as some others, can be scheduled to commence in sequence at one end of the project and progress toward the other end

The development of lead/lag techniques has added to the basic network modeling improved representation of overlapping activities such as activities in linear projects, is thus available with network analysis approaches However this additional complexity and the effort required to develop and update complex networks have discouraged the use of the method for linear projects (Johnston 1981) Like bar charts CPM networks do not represent location or productivity information (Figure 2-3)

Relationship Shown Schedule Type	Activity	Job-Logic	Time Uncertaint	Production Rate	Activity Location	Resources-Time
CPM		▨				
PERT		▨	▨			
Bar (Gantt) Chart	▨	▨				▨
Quantified Bar Charts	▨					▨
Time Scaled Logic Diagram	▨	▨				
Line-of-Balance	▨	▨		▨	▨	▨
Multi-Activity Chart	▨	▨				▨

Figure 2-3 Capabilities of scheduling techniques

2.1.3 Linear Scheduling

An awareness of the fact that the traditional network is not the best tool for the planning of linear projects and the shortcomings of bar charts in today s complex world has led to a resurgence of interest in techniques to assist in planning these projects (Handa, Barcia, 1986) The techniques that have been developed are generally referred to as linear scheduling methods

Projects that are generally characterized as linear may be divided into two categories. The first includes projects that are linear due to the uniform repetition of a unit network of activities throughout the project. Multiple housing projects involving the repetitive construction of similar houses are a good example of this category. The second category includes projects that are linear essentially due to their physical layout. Highway projects, tunnels, railroads, and many transportation projects are excellent examples of this category. These projects are generally not characterized by the uniform repetition of a unit network and generally involve a number of activities that are discreet in nature.

The execution of the linear activities is often not in a uniform fashion from the start to the end of the project (Vorster, Beliveau, Bafna 1992).

Graphical techniques such as the linear scheduling method and the time space scheduling method have been successfully used to plan and schedule projects of this type. Gorman was among the first authors to suggest the use of a time versus distance diagram (Gorman, 1972) to achieve better communication of schedule information through visual impact in rapid transit, highway and pipeline projects. This diagram had location on the x-axis and the time on the y-axis.

2.1.4 Resource Allocation

Resources are defined as anything consumable (except time) that is required to accomplish an activity, such as labor, materials, equipment, etc. Resource requirements are estimated at the activity level based on the project/activity documentation and achieved productivity or production rates under the stated environmental and managerial conditions. The availability of resources plays a major role in balancing project resource requirements.

Project managers are utilizing resource histograms to balance the projects with limited resources. A histogram is a graphical display of the amount of resources required and/or available as a function of time on a graph. In linear scheduling, each activity on the project schedule can be associated with the work of one particular crew. Because of its strong link between activities and crews, linear scheduling increases the planners awareness of resource constraints. The problem of placing one crew in two places at the same time is likely to be avoided. The project manager can make necessary changes to the linear schedule diagram or to the amount of resources in order to ensure the most efficient use of the limited resources.

2.2 Currently Available Scheduling Software

Scheduling and planning are performed with computers by a surprisingly low percentage of the construction industry. In this area there is a lot of well-developed software that could offer many advantages. A survey performed in Sweden, Denmark, and Finland showed that 14% of contractors perform all planning manually and only 10% use computers all the time (Samuelson, 2002). Architects and engineers surveyed use them more as 27% of engineers perform planning with computers all the time.

One of the earliest computer applications in construction was the critical path scheduling. Several of the more popular scheduling programs are described below to demonstrate the level of development required of any linear scheduling program.

Primavera Project Planner (P3) is one of the most popular scheduling programs used today in the construction industry. It has a maximum capacity of one hundred thousand activities on a single project, plus the ability to group projects together. Templates made from similar projects and the use of various assistants or wizards facilitate the creation of schedules. It allows the writing of subroutines to automatically input or modify activity information that speeds up the development of schedules. Global changes are permitted. P3 offers two hundred reports and related graphic representations Module attachments to P3 provide additional project management tools for reports, cost control, resource management, and estimating. The main drawback of P3 for most construction companies is the high cost of the program that reaches several thousand dollars

SureTrak Project Manager by Primavera is similar to the Primavera Project Planner. It provides almost the same functions as P3 for only several hundred dollars, as it allows a maximum of only ten thousand activities on a single project, allowing no global changes. It consists of forty pre-programmed reports and related graphic representations. Accessory modules are not available for SureTrak.

Microsoft Project is a scheduling program preferred by many construction companies. Its popularity is greatly attributed to its ease of use and similarity to other Microsoft programs. It provides most of the functions and features as the more expensive programs and allows a maximum of ten thousand activities. Twenty pre-defined reports and graphic representations are included. Microsoft Project sells for several hundred dollars

2.3 Development of Scheduling Techniques for Repetitive Processes

It is generally recognized that application of procedures to improve planning, scheduling, and control of construction projects can provide many benefits (Johnston, 1981) for both the client and the contractor, benefits that can be finally extended to the whole society. Reductions of overall costs, increasing safety, and shortening project duration are only some of them (Rowings, Rahbar, 1992)

From all the types of construction projects, transportation projects like roads and highways are characterized by the high repetitiveness of the construction activities, because of their linear nature This characteristic translates in requirements for schedules that should ensure the uninterrupted usage of resources from an activity in one unit to a similar activity in the next unit (Harris, Ioannou, 1998)

The use of typical critical path method (CPM) techniques by the construction planners, which are faced with this type of projects, may fall short in accurately representing them when continuity of resource usage is desired (Harris, Ioannou 1998) In order to model more precisely such resource-driven projects, the linear scheduling method (LSM), has been developed

The technique is known under different names as

- Repetitive Scheduling Method (RSM)
- Line of Balance (LOB)
- Vertical Production Method (VPM)
- Time-Space Scheduling
- Cascade Networks
- Chain Bar-Charts (Arditi Abulak, 1986)

Harris and Ioannou also mention some other names given to this method

- Construction Planning Technique (CPT)
- Time Location Matrix Model
- Disturbance Scheduling
- Horizontal and Vertical Logic Scheduling for Multistory Projects (HVLS)

They also identify that in projects where progress is measured in terms of horizontal length names like Velocity Diagrams or Time Versus Distance Diagram have been used.

Arditi and Abulak (1986) stated that the origins of LSM are not clear and it is possible that LSM had multiple origins in different countries The wide variety of names and approaches to scheduling linear projects has multiple or parallel origins However, these variations are based on common features repetitive units of work and known or estimated rates at which these units will be produced (Rowings, Harmelink 1995) and scheduling the work in a project by plotting the progress of repeating activities against time (Harris, 1996)

The members of a group headed by George E Fonch devised the Line of Balance (LOB) method During 1941 the Goodyear Tire and Rubber Company monitored production with LOB (NNH Enterprise 2000) Ten years later, U S Navy is known to have used the LOB technique to plan and monitor the progress of industrial processes (Department of the Navy, 1962)

In April of 1962 the Office of Naval Material under the Department of the United States Navy describes the LOB technology as follows

> Line of Balance is a technique for assembling selecting, interpreting and presenting in a graphic form the essential factors involved in a production process from raw materials to completion of the end product against a background of time It is essentially a management type tool utilizing the principle of exception to show only the most important facts to its audience It is a means of integrating the flow of materials and components into manufacture of end items in accordance with phased delivery requirements.

The objective of this method was to determine or evaluate the flow rate of finished products in a production line (Sarraj, 1990).

The output for the LOB technique has three components which are often plotted as follows

1 A unit network which shows activity dependencies and time required between activity and unit completion

2 An objective chart showing cumulative calendar schedule of unit completion

3 A progress chart showing the completion of the activities of each unit (Carr, Meyer 1974)

The unit network shows the assembly operations for a single unit of many to be produced (Johnston, 1981) It also uses time for the horizontal axis and some measure of production on the vertical axis The objective of the Line of Balance unit network is to schedule or record the cumulative events in the completion of a single unit (Rowings Harmelink, 1995) This approach might be used in planning the construction of a multi-story building for example, the single unit may be a hotel room or an entire floor

The progress diagram in the LOB technique is prepared as a bar chart The bar represents the units produced on a particular day which is compared to the LOB to determine if the process is on behind or ahead of schedule

Carr and Meyer concluded in 1974 that the LOB method could be useful in the construction of repetitive building units In their 1986 review Arditi and Abulak identified several failings of LOB when applied to construction In particular they point out that extreme care must be taken in the estimation of production rates as the method is sensitive to errors in the activity duration estimates They also recommend careful selection of the drawing scale and using multiple colors to improve legibility of the schedule (Arditi Abulak, 1986)

In 1990, Sarraj developed and presented algorithms that resulted in a mathematical line of balance model According to Sarraj using this method in its mathematical form enabled the development of production and delivery schedules without drawing a diagram, the graphical representation was merely used for illustrative purposes in the process of project control (Sarraj, 1990)

Figure 2-4 depicts an example of planning and scheduling a manufacturing process by using the line of balance (NNH Enterprise, 2000)

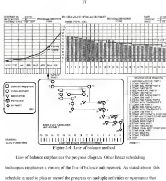

Figure 2-4 Line of balance method

Line of balance emphasizes the progress diagram Other linear scheduling techniques emphasize a variant of the line of balance unit network As stated above this schedule is used to plan or record the progress on multiple activities or operations that move continuously in sequence along the length of the project

For simplification and visualization purposes most of the researchers assumed that there is continuity in crew's work, which move from one area to the next one, without considering parallelism (two or more areas being worked at the same time by different crews)

Since the 1970 s a number of linear techniques other than line of balance have been developed and explored academically for application in the construction industry

Johnston describes in his 1981 report a method known as the Construction Planning Technique. This technique is used to determine a schedule from what the planner determines to be critical (eg. economic considerations or resource limits) rather than determining the critical path from individual activity durations. The input of this technique is based on production data (Rowings, Harmelink 1995). Other than comment by Johnson in 1981 this method has received little more than inclusion in historical chronologies since the mid-70

Because of the similarities in constructing floors in high-rise buildings, and also due to the fact that the linear nature of a project may not always be horizontal, the Vertical Production Method was proposed in 1975 by O Brien for scheduling repetitive units. He adhered to the use of the critical path method for scheduling components such as foundations, site work, and structures in the first typical floor since most of these activities were discrete. The rest of the project comprised of nearly identical floors (O Brien 1975). One floor is chosen as a prototype while the rest of the work is presented for a unit network for a typical floor (Vorster, Beliveau, Bafna, 1992). The schedule is controlled by how long it takes for major trades (crews) to move through the building bottom to top (O'Brien, 1975). This model appears to be simply a specialization of the more general linear schedule model which may be used for horizontal work as well.

It is accepted that the Vertical Production Method is essentially a linear scheduling method even though it progresses vertically (Johnston, 1981).

Another technique that can be applied to the scheduling of linear construction projects due to their similarity to assembly line manufacturing is the Ranked Position

Weight Technique (Handa, Barcia, 1986) This method was reported by Helgeson and Bernie and is used in assembly line balancing (Helgeson, Bernie, 1961)

Each work item is appointed a weight, which defines its position relative to the others in a descending order The positional weight is defined as the sum of the operating time required for that element and the times for all elements that must follow that element (Handa, Tam, Kwartin 1992) Using these positional weight values, the elements are ranked in descending order and once a desired production rate is determined, the cycle time can be calculated

When using the Ranked Positional Weight Method two types of constraints are used precedence constraints, and technological and zoning constraints (Handa, Barcia, 1986) To demonstrate the method Handa and Barcia use as an example a project found by Clough (Clough 1972) Handa and Barcia claim that the method is simple, that it can be applied on site, and that it has the critical path as a by-product. For that reason, this method is important to the resource scheduling and the project planning personnel

Other variants of scheduling techniques were proposed in the early 1980's. Like the Construction Planning Technique of the 1970's, these variants sought to optimize resources and/or minimize time, determining durations as the schedule is developed These methods generally follow the "flow" of work crews rather than (or as well as) following the chronology of activities.

Johnston described a method he felt especially suitable for highway construction in 1981 This schedule included graphical representations other than diagonal lines he also allowed for varying production rates (Johnston, 1981) Whether they were developed parallel or as a result of Johnston's 1981 description, most subsequent study of linear scheduling techniques that are of any practical use follow the same general theme.

Another graphical technique, which, as mentioned earlier, is suitable for the management of linear type projects, is the Linear Scheduling Method. There are a few different ways of representing the two-dimensional result of a Linear Schedule, and that will be mentioned in the next chapter

A diagram which had location on the x axis and time on the y axis was presented as a "time versus distance diagram" by Gorman (1972). This way, schedules for highway, and pipeline projects would convey a surplus of information to the examiner

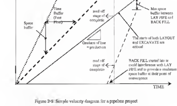
WORK
Time
LAYOUT
EXCAVATE
LAY PIPE
BACK
Time Buffer (Free Float)
Space buffer
read off stage of completio
Min space buffer between LAY PIPE and BACK FILL
Gradient of line = production
The starts of both LAYOUT and EXCAVATE are critical
read off stage of completio
BACK FILL started late to avoid interference with LAY PIPE and to provide a minimum space buffer at their point of convergence
TIME

Figure 2-5: Simple velocity diagram for a pipeline project

Peer and Selinger (1973) developed a method called the Construction Planning Technique (CPT) while analyzing parameters affecting construction time in repetitive housing projects. They identified nine steps to be taken during the construction planning process.

Carr and Meyer (1974) applied linear scheduling to building construction.

Clough and Sears (1991) emphasized what is essentially a linear scheduling diagram. In their example, straight lines on a graphical layout having location on the horizontal axis and time on the vertical axis represented the schedule of a pipeline relocation project. A linear scheduling diagram was also presented by Barrie and Paulson in 1984. It was called the Linear Balance Chart (Barrie, Paulson, 1992).

Thomassen (1982) also gives some examples of the use of linear scheduling for construction projects.

Stradal and Cacha (1982) presented a variation of linear scheduling called time-space. They suggested using this method in linear projects, in completion to others. They also presented and discussed examples of building construction, pipelines and highway construction, mentioning the usefulness of the method for flow line type of projects.

At his turn, Parvin (1990) has presented to the professionals a set of three video tapes which show the steps involved in drawing a linear schedule. The videotapes also show how to use the linear schedule to manage construction and resolve delay claims. A few case studies are part of the material included in the third of the videotapes.

The research done in 1991 by Bafna, while trying to extend the LSM on highway projects, resulted in a number of advancements to the technique that exploit the simplicity and it's graphical nature. He also emphasized the importance of visualization and the role of LSM in planning, execution and control phases of a construction project.

Johnston (1992) discussed the basic elements and concepts of linear scheduling in his publication He used a graph that showed location on the y-axis and time on the x-axis In that graph, activities were plotted diagonally with a positive slope denoting the production rate Later Johnston and Chrzanowski applied the linear scheduling method to schedule a roadway project located in North Carolina The results of this effort were also discussed.

In 1992, Rowings and Rahbar proposed a new approach for Linear Scheduling of Transportation projects by developing a procedure called Repetitive Activity Scheduling Procedure (RASP) The basic elements of working and understanding RASP are

- Work breakdown structure (WBS), by separating the project into the constituent component processes
- RASP worksheet, in which all the components of the WBS are listed
- RASP schedule format which is the graphical display of the project plan showing activities' time and location all framed in one picture

The advantage of this technique is its simplicity and the fact that the RASP schedule format and worksheet can easily convey detailed information that is comparable with what may be derived from an equivalent CPM schedule

Rowings and Harmelink (1995) presented the development of a linear scheduling model with microcomputer applications for highway construction project control

Subsequent work was reported by Russell and Caselton (1988), Sarraj (1990) Moselhi and El Rayes (1992), Vorster Beliveau and Bafna, (1992), and Russell and Wong (1993) Some of this work did include the application of time-cost analysis to the schedule (as is currently done with CPM-based software models by Primavera Microsoft and others)

One of the most recent studies was done by El-Sayegh (May 1998) who, in his PhD dissertation, develops the Linear Construction Planning Model (LCPM) both, in a deterministic and probabilistic way. In his research he develops a deterministic resource-based model for planning and scheduling linear construction projects. His model combines the visualization capabilities of linear models with the numerical capabilities of network models. The new approach consists in scheduling of both discrete and continuous activity types, and in incorporating the uncertainty of production rate estimates in the scheduling algorithm.

In order to simplify and generalize other various scheduling procedures, mainly the CPM network, which is considered too complex for scheduling multi unit projects, Harris and Ioannou proposed the Repetitive Scheduling Method (RSM). This method applies to both vertical and horizontal projects containing either discrete or continuous activities, and is presented graphically as an X Y plot of a series of production lines, each representing a repetitive activity. The authors emphasize that the RSM introduces a new concept for positioning successive production lines, which are the control points between them, located either toward the first or the last unit in the sequence of units, depending on the convergence or divergence of lines.

The previous concept is derived from one of the basic principles of planning and organizing construction activities, which is synchronizing the activity of the working crews. This principle recommends that a crew should begin an activity exactly after the previous crew has completed the preceding activity.

In recent years, the most significant work appears to have been by researchers at the University of Iowa and at Virginia Tech. The RSM has also been an area of significant interest at the University of Florida in recent years (Sims 1998). This recent work is the basis for the scheduling method presented in this dissertation.

These techniques appear to have received little interest outside the realm of academia; this is in spite of efforts by the academicians to foster commercial acceptance of the linear scheduling methods since the late 1980's. However, it is generally due to a failure on the part of government agencies (as owners) to recognize the benefits of linear scheduling and to adopt its use, and is also due to a failure on the part of software companies to develop commercially viable linear scheduling products.

2.4 Survey of Current Practices

A survey of each State's Department of Transportation was conducted by to determine which DOT's are currently using the linear scheduling method (LSM) as a scheduling method in their construction operations, and to ascertain the level of knowledge of the LSM that is available within the DOT's (Herbsman, Glagola, Cosma et al., 1999). The results, as reported in Appendix A, were received in late 1997 and early 1998.

Thirty-seven DOT's responded to the survey, with a response rate of 73%. Of the 37 respondents, only two (Connecticut and Texas) stated that they are using the LSM in their construction operations, particularly in claim analysis, while Georgia DOT is only considering trial use with some projects. Virginia DOT reported the use of LSM as a contractor's option.

Another three DOT's (Nebraska, Oregon, and Pennsylvania) reported that they are using the LSM, but further analysis of their responses revealed that they are actually using bar charts and/or CPM's as their scheduling method, or SureTrack (Utah)

Almost sixty-five percent (65%) of the respondents are not familiar with the LSM and twenty-seven percent (27%) are only somewhat familiar with it Only three DOT's (constituting 8%) are very familiar with this scheduling method (Figure 2-6)

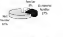

Figure 2-6 DOT's familiarity with LSM

Even if some DOT's admit that most of their projects have a linear nature, they consider that parallel activities which are also an important characteristic cannot be properly scheduled They also consider that it would be even less advantageous for the owners to try to "make it fit all" (California)

Colorado DOT took some steps in training their personnel in LSM, but even after reviewing some video tapes on the subject, they didn't considered it necessary to be implemented The mentioned actions are ten years old Since the late '80s (or early 90s) no other interest has been reported on this subject.

Pennsylvania DOT also reported conducting 3-day training seminars for the personnel on an ongoing basis, not on linear scheduling but on CPM Actually they developed their own method and software that imports the data by the contractor and puts it in a useful graphic with the help of which they monitor schedule progress daily, and also measure the production output The scheduling techniques are viewed as very useful communication tools for transmitting goals to the field level personnel

Other DOT's, even if not currently using linear scheduling, expressed their interest on any information concerning this technique (Delaware, Vermont, Washington). This interest made the investigators conclude that there is a significant gap in information and knowledge concerning the efficiency and suitability of planning and scheduling techniques, and the types of construction projects. Even if the academic research has taken significant steps in this direction, for various reasons the information didn't get to the designated user that is the construction industry.

Quite contrary, some DOT's reported that they have looked at the concept of linear scheduling, but not seriously enough.

Spreadsheets like LOTUS or planning programs like MS Project, Primavera, Sure Track, Artemis Planning 9000 and Schedule Publisher are some software programs used in assisting the scheduling process. Some DOT's even blamed the lack of software as one of the reasons for not using linear scheduling (Iowa DOT and Florida DOT).

Several DOT's consider that it is the contractor's responsibility to suggest the proper scheduling techniques to be adopted. They admit that generally, when contractors have provided schedules it has been easier to identify the delays much earlier, to assess the contractor's performance, take action to limit liabilities, and finally to resolve claims. Investigators noticed that preventing, and mainly resolving claims is seen as one of the most important uses of planning and scheduling techniques. The reason is a construction industry plagued by claims and disputes, doubled by an increasing difficulty in reaching reasonable settlements in an effective, economical and timely manner.

As shown in Appendix A, no state DOT uses LSM as a matter of course (whereas some states, such as Florida, in fact require the use of CPM). The confusion made by some DOT's between LSM and CPM or bar charts might indicate a lack of knowledge concerning the scheduling techniques as well as poor training of the personnel from the planning and scheduling division. The investigators presume that the confusion rests strictly with the respondents to the questionnaire. Further investigation would be needed to establish the familiarity with the LSM scheduling technique at other organizational levels.

Based on the title of the respondents a secondary analysis has been performed (Figure 2-7) in order to establish the level of information and knowledge of different contractor representatives.

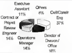

Figure 2-7. State DOT survey results-secondary investigation

Due to the above results, the investigators suggest training on planning and scheduling techniques and software, at all organizational levels, as a first step in familiarizing the DOT personnel with these techniques. However several states such as Connecticut and Texas use LSM in their claims analysis, while other states such as Georgia are only considering trial use with some projects. The data also indicates that a number of contractors, given the choice, use LSM vice CPM.

The data seems to indicate that there is definite interest in using LSM in the highway construction industry however there are insufficient familiarity and no apparent driving force to encourage more widespread use

2.5 Other Research

A research done in 1993 by Rowings, Harmelink and Rahbar and sponsored by the Iowa DOT, concluded that highway, railroad or pipeline construction projects, characterized by a strong linear orientation These types of projects appear to be good candidates for the linear scheduling technique The report also proved that linear scheduling is more affective than the critical path method for this particular type of projects, either because of the lack of control information or due to the overly complex process, that make CPM or bar charts not appropriate

The real world conditions and constraints encountered in transportation projects make properly modeling a very difficult task Transportation projects are characterized by a high variance in size and type Using CPM while small projects may require only a bar chart to identify the work items can properly plan large bridge projects

The researchers consider that CPM introduces a rigid logic which doesn't exist in reality in transportation projects. In order to select the proper planning and scheduling technique Rowings Harmelink and Rahbar consider that an analysis of the project characteristics and needs has to be done as a first step as the scheduling procedures must be developed and tailored to each specific project according to its type size and complexity

Still, because transportation projects are actually not as linear as they appear (i e earthmoving activities do not move smoothly from station to station the entire area being worked until a subgrade is achieved) and also the substantially variance of the daily construction productivity the use of Linear Scheduling is to be based on several assumptions. One of these is that the rate of the output will be uniform

The researches also conducted a survey on the various state DOT's, in order to establish the approaches used by them to determine contract durations control time and to schedule resources for annual construction program The research reveled once again that CPM and bar charts are the main scheduling methods required from contractors by the districts of transportations

The research concluded that a large number of projects have specific characteristics that dictate a different approach than the bar chart and the CPM The alternative would be using the principles of linear scheduling mainly because of its simplicity The visual cue provided by this technique allows scheduling information to be displayed in a format that is easily understood by all parties involved in a project.

Also the case study done with a linear project on Interstate 29 in 1992, helped the researchers to compare the as planned schedule, developed from the CPM by the contractors to the as-built linear schedule for the project There was evident that the linear project's predilection for activities with variable production rates was much easier to handle and visualize with the linear technique than with CPM

Although there are advantages of using linear scheduling, one of the major problems in implementing this technique was identified during the research as being the multitude of different specifications for highway and bridge construction between the state DOT's A group of 26 states were found to have similar specifications that typically required the contractor to furnish the Engineer with a progress schedule (or CPM) showing the order of the work and time required for the completion. The schedule is to be used to establish major construction operations (or salient features or control items) and to check progress Another significant number of states were also found that had specifications different enough from the previous group to warrant separate treatment

In 1995 Rowings and Harmelink continued the research and developed a Linear Scheduling Model and compared it to the conventional CPM scheduling techniques finalizing the research with routines developed in AutoLISP in order to allow AutoCAD to perform LSM tasks. At the basis of this routine stayed two research projects that have been completed for the Iowa Department of Transportation (IDOT)

The results of the first project (1993), in which the linear scheduling technique was applied to a highway construction project currently in progress indicated that the linear scheduling method merited further investigation. The second research project (1994) allowed the research team to evaluate LSM on a small diverse group of three projects

The researchers compared CPM scheduling to LSM, comparison that produced some interesting results. They discovered that the linear schedule helps visualizing all the logic errors conflicts in location or other omissions that appear in the original CPM schedule They also emphasized that all possible relationships were very difficult to describe using CPM thus making the schedule less accurate A comparison between needed and existent capabilities of the two analyzed scheduling methods is presented below

After comparing the two scheduling techniques(Table 2 1) the researchers concluded that the first step in imposing linear scheduling as a widely accepted planning and scheduling tool would be to develop a rigorous analytical model capable of providing all the necessary scheduling functions A second one consisting of the computerization of the linear scheduling technique should follow this step

Table 2-1 Capabilities of Linear Scheduling versus CPM

Needed capabilities for LSM	Existent capabilities for CPM
Determine the controlling activities	Highly developed computer applications
Determine the controlling activity path	Rigorous analytical capabilities
Identify non-controlling activity segments	Widely used
Establish and measure activities floats	Widely accepted as a scheduling method for a wide variety of projects
Provide means to status activities	
Provide means to update projects	
Capture as-build data	
Construct as-build project schedule	

In one of the most recent analysis of scheduling techniques, Yamin and Harmelink compared CPM and LSM by looking at important project management attributes facilitated by CPM and LSM, (Yamin, Harmelink 2001)

Another conclusion was that planning is facilitated using LSM because it is visual and intuitive and also for linear and continuous projects LSM is superior to CPM At its turn, CPM is a more complete scheduling tool than LSM mainly because multiple resource management techniques and statistical analysis have been developed for it

The attributes considered by Yamin and Harmelink in their comparison were

1 Aid in reduction of uncertainty/risk

CPM Although CPM schedules use fixed durations for activities, it can be easily complemented by PERT with statistical capabilities This feature helps planners to get a better idea of time and schedule risks

LSM: There is no formal method developed to date that could allow LSM to determine uncertainties in time completion

2 Aid in improving production and economical operation

CPM: With the incorporation of resource leveling / allocation techniques, CPM schedules can improve the overall completion time costs by affecting production (add or remove resources) Some limitations have been identified when scheduling continuous projects difficult to maintain continuity in crew utilization

LSM: Limited capabilities in improving production by changing resources Easy to schedule continuity on linear projects improving coordination and productivity

3 Aid in achieving better understanding of objectives

CPM: In complex projects CPM network can be very convoluted This complexity makes them difficult to understand and communicate

LSM: Very easy to understand and can be used at every level of the construction project

4 Accurate calculations

CPM: CPM allows the PM to calculate time it would take to complete a project and together with PERT could provide statistical insights to this process It is difficult to accurately determine and represent space restrictions (if any)

LSM: Location/time calculation is easily done This is the greatest advantage of LSM over CPM when scheduling linear projects This capability allows PM to accurately plan activities both in time and location

5 Critical path

CPM: It is the main feature of the CPM which can be done very easily

LSM: The LSM algorithm calculates the controlling activity path (CAP) which is equivalent to the critical path, with the additional feature of location criticality

6 Ease of use

CPM: Extensive computerization has made the CPM method easier to use. However, the user needs a considerable amount of training before actually being able to produce valuable information for controlling purposes.

LSM: Very intuitive and easy to understand. It can be used at all levels of the company (managers, superintendents and crew). Lack of computerization makes it difficult to use in large and complex projects.

7. Easy to update

CPM: The method could be difficult to update. Once several updates have been done, it becomes difficult to read. Updated schedules are usually out of date when they are finished.

LSM: Updating LSM is simple. Linear schedules can be used as as-built documents for claim purposes or for historical productivity databases.

2.6 Review of Current Software on Linear Scheduling

2.6.1 TransCon XPosition

TransCon XPosition is a linear scheduling software developed by TransCon Consulting Ltd., (1997), a Richmond, Virginia based firm. This software is compatible with any computer that has Windows 95 or Windows NT operating systems.

The software makes use of drawing components of LSM in order to facilitate plotting of the linear schedule. These components are: Axes and Sight Lines, Access Constraints, Bars, Lines, and Blocks.

The TransCon is more a drawing software because the user has to know for each activity the start and the finish dates together with the start and finish locations. By using TransCon Xposition it is possible to print or plot the schedule to any printing device supported by Windows 95. The user can also print the tabular activity data to be included with the schedule.

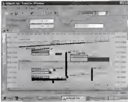

Figure 2-8 TransCon Xposition output

The main advantage of TransCon Xposition software is that it allows visualization of the plan of construction operations by using the basic components and graphical symbols of linear scheduling (Figure 2-8), thus providing time/space portrayals that are easier to communicate and understand in comparison to other scheduling tools.

The software also has some disadvantages, the main disadvantage being that the program is more a graphical tool than a planning and scheduling tool. The program does not calculate the finish date of an activity; the user has to input both the start and the finish dates. TransCon does not help the user to calculate the buffer spaces between the adjacent activities. Also, it does not consider one of the most important elements in scheduling, which is the productivity rate of an activity. All the above elements have to be calculated in advance by the scheduler, who will introduce them as input data in the software. This involves repetition of work by the scheduler thus increasing the total time taken to schedule the project

2 6.2 Line of Balance Planning by Spreadsheet

Spreadsheets like LOTUS Excel, Quattro Pro can be used as general purpose packages in applications that would have required a specific program a few years ago

The spreadsheet can help the planner in manipulating and interpreting the quite heterogeneous data in order to plan and schedule linear construction projects

The user has to write formulae to calculate the buffer between the adjacent activities and the start days for units 1 and N (units being piers in case of bridges, floors in case of buildings, etc) of each activity The user will also have to input a formula to determine the type of buffer whether start or end buffer Start and end dates of each activity are calculated by the computer depending on the type and the value of the buffer All estimated buffers are calculated as being 20% of t the justification of this being that the accuracy of estimation of activity duration is believed to be ±20%. Through the dominance of IBM-compatibility and MS-DOS, data can be easily exchanged between the various standard programs. In many cases, it is much easier to use standard packages to produce a more limited solution more quickly and with less effort. It is more beneficial for users to learn how to use packages of general application than to have to learn how to use a special program for each application

A further practical benefit of this program is its flexibility The data, which is available in a large variety of forms, can be easily manipulated and used in the calculation of the line of balance schedule by using the spreadsheet By using the spreadsheet, buffers between activities can be calculated automatically because they are related to the activity durations

The durations of each activity are those thought most likely to occur using the firms usual method and not considering the productivity rates The spreadsheet does not take into consideration the man-hours per unit theoretical crew size, man per item of construction and rounding to an integral number, actual rate period etc Therefore more work is involved in making another spread sheet so as to include all the above whenever required

The main disadvantage of using this program is that it considers that the activity production rate is the same for the whole space, it does not consider subdivision of locations in stations and sections, which is very common for linear construction projects This program is useful for projects of a successive nature, i e one activity starts only after the finish of the previous activity and that no two activities run simultaneously Therefore, it is not suitable for projects which are not successive in nature.

Access and weather constraints are also not considered The program solves the buffer problem between two consecutive activities which is one of the most important problems but only if the location is one section.

2.6.3 Line of Balance (LOB) Scheduling Program for Windows

The LOB program for Windows is a self-installing stand alone computer application for linear construction scheduling The program builds a schedule based on the production rates of a sequence of operations performed along a linear track through the project To use the basic scheduling functions of the program, the user needs to only have a project with a defined number of sections a list of operations, and the production rate for each operation in days/section. Installation of the program can be accomplished with a Windows File Manager

The program calculates calendar start and finish dates based on a standard five-day workweek. The mathematical start and finish days (work days) of the operations are determined by the computer using linear construction scheduling formulae.

The main output of the program is a graphical line of balance schedule, which can be viewed prior to printing, by clicking on the "View Graph on Screen" button at the top of the Print Option Screen. The time scale of the graph is in terms of workdays. The program can also plot as an output the resource histogram, and a standard bar chart which has the time scale in calendar days.

Some of the advantages offered by this program are

- Automatic save feature built-in.
- Tracks up to four different resources for each operation.
- Print resource histograms
- Update/As-built function allows user to input actual completion of each operation and print schedules forecasting start and finish dates for remaining activities based on the dates of completed activities.
- Built-in holidays and non-workdays, which the user may edit.
- The feature of previewing the graphical schedule prior to printing allows the user to play out various "what-if" scenarios without using up a lot of paper

The main disadvantage of the program is that it uses days/section as the production rate, whereas, the actual definition of this parameter is output unit/working days, representing the production output of a given crew during a unit of time. The so named production rate is actually the duration of the operation. By confusing the actual production rate with the activity duration, the program is not considering the quantity, the crew size and the real production rate and their influence on linear scheduling

Even though the program considers the subdivision of the location into sections it does not solve the problem of buffers between adjacent operations at each section The buffers are considered only at the start and end sections

The resource histogram as offered by this program does not have a bar chart presentation Daily resources are given in the form of numbers at the bottom of the graphical line of balance schedule this being difficult to visualize and analyze by the scheduler

2 6 4 Linear Construction Project Manager (LCPM V1 0)

LCPM V1 0 is a prototype of a planning and scheduling software for linear construction projects such as highways and pipelines The software was developed as a tool to assist in performing the calculations required in using the Linear Construction Planning Model (LCPM) which is a model proposed by Sameh Monir El-Sayegh in his PhD dissertation for planning and scheduling linear construction projects

LCPM was developed using the Microsoft Access 2 0 database package In order to ease the reference storing and sorting capabilities and also the ability to link to other existing company's information a database structure is used to develop this prototype

One of the functions that LCPM performs is to store in tables information about equipment, labor, materials, and crew mix and crew types. This part is called dictionaries and the user is allowed to view and edit the data in these dictionaries at any time. Another function performed by LCPM is scheduling construction works The user has to enter specific information about the project, and once the project data are input, the schedule is calculated based on which graphs and reports can be generated. LCPM has a user friendly interface and minimal knowledge of computers is needed to operate it.

The software requires the user to input the data into the dictionaries and also data for the scheduling. The data stored in dictionaries is used to calculate work item duration costs and some reports. The dictionaries include equipment, labor, materials, crew mix and crew types. For the first three resources, i.e. equipment, labor and materials, the user will input data using three main fields, which are: code, description and cost. The crew mixes are formed by using the "Crew Mix" form which contains the crew mix code, description, equipment, quantity, labor and quantity of labor. The crew types are to be inputted in a "Crew Type" table, which consists of five fields; these fields are, the crew type code, the crew description, crew mix code, daily linear production rate (LPR) and unit of distance measurement. The crew mix table and crew type table are related such that a crew mix can be assigned to more than one crew type, while crew type can have only one crew mix.

In order to do the scheduling, the scheduler will input the data in a step by step manner. The scheduler will input all project information and calculate the schedule before viewing the reports and graphics or starting the probabilistic scheduling algorithm. The user has the option of either using the probabilistic schedule or the deterministic schedule, depending on the degree of uncertainty in the production rate estimates. The outputs from this software can be either graphical reports or tabular reports. The tabular reports generated by this software are:

- Crew Types
- Equipment Classification
- Labor Classification
- Schedule Report by Activity
- Schedule Report by Work Area
- Schedule Report by Early Start
- Simulation Results
- Crew Movement Report

- The graphical reports of the schedule information are the following
- Linear Schedule
- Crew Movement Chart (for crews 1 to 6)
- Crew Active and Idle Times

Each graphical report contains a pie chart that shows the idle and active time percentages for the specified crew

The LCPM V 1.0 prototype has a few advantages The software allows the scheduler to schedule the linear project, both deterministically and probabilistically The prototype has a user friendly interface, it uses forms as a way of displaying data and command buttons for navigation through the application. Minimal knowledge of computers is needed to operate this software Another advantage of the software is that the project is divided into work areas thus considering the different production rates for each activity on the different sections Also, project control is made easier by this dividing of location

The software also has some disadvantages The problem of the buffer time between two consecutive activities remains with the user The software has no algorithm to solve this problem. The program does not consider the calendar days, holidays and other constraints that might appear during construction The software does not show a graphical output for resources other than labor It also does not show cash flow charts and S-Curves used to facilitate cost management and control

2.6.5 Florida Linear Scheduling Program (FLSP)

Even if Linear Schedule can be calculated manually for small construction projects, there is a need for computer software to perform the calculations and prepare the charts, tables and histograms for larger linear construction projects (having more than 50 activities)

The Florida Linear Scheduling Program (FLSP) is a prototype of a planning and scheduling software for linear construction projects such as highways and pipelines. This software was developed as a tool to assist in performing the calculations required in using linear scheduling.

FLSP has two functions: the first function is scheduling a specific linear construction project by using the linear scheduling method and the second function is to perform resource management. The software has a user-friendly interface. Minimal knowledge of computers is needed to use this software.

The output capabilities of FLSP v1.0 are

- Linear Schedule Graph (Figure 2-9)
- Resource Histogram
- S-Curves

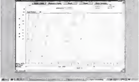

Figure 2-9 FLSP screen

2.6.6 PlaNet+

PlaNet+ has been developed especially to meet the Finish project management's needs (Saros, 1996). PlaNet+ includes location-timesheet, in which planning of repetitive tasks is illustrative and easy. The location break down can be determined either in one or two level. User can choose needed tasks to be displayed in location timesheet. Tasks can be divided into parts, modified, scheduled, and overlapped easily either in bar chart or in location-timesheet - and thus the work can be implemented without interruptions.

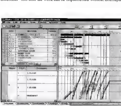

Figure 2-10 PlaNet+ output

In print preview the user can view the schedule either in one page or can divide it into several pages. After examining the schedule the user can decide whether he/she wants to print the location-timesheet or the bar chart. Charts can also be printed one below the other, in which sum tasks are displayed in bar chart and the modified schedule of work's progress is displayed in location-timesheet. The schedule can be illustrated by using different colors, patterns and adding line descriptions (Figure 2-10).

2 6 7 Purdue University Linear Scheduling Software (PULLS v1 0)

PULLS is a prototype software that was developed within a Computer Aided Design (CAD) environment PULLS allows the user to visually create linear schedules and it also automated the calculation of the controlling activity path (CAP)

The four steps for creating the linear schedule for calculating the CAP are as follows (Harmelink, Yamin 2000)

- Introduction of general project information like start date start and end stations working days etc
- Creation of activities by selecting the type length and direction of the activities Activity duration can be introduced in three different ways by either providing the total duration of the activity by providing the start and end dates of the activity or by providing the productivity rate of the activity
- Calculation of the activity sequence that will be done by PULLS after the user clicks on the "Calculate ASL" button.
- Calculation of the controlling activity path which will give as an output the CAP draw for the schedule in color red using a different layer from the previous step

One of the limitations of PULLS is that it cannot calculate the controlling activity path (CAP) if there is a time period where there is no activity being executed in the project. The researchers that developed the software recommend to use a bar activity in order to represent such time of no activity A second shortcoming of PULLS is that it does not differentiate between intermittent and continuous activities All activities are considered continuous for the CAP calculation

The two construction companies contacted by the researchers in order to test the PULLS software prototype offered an interesting feedback. The prototype was considered not to be very user friendly Contractors also suggested to include multiple productivity rates in schedules and also to include space restrictions as a "third" dimension for the scheduling jobs because it directly affects productivity and the way the job is scheduled. Contractors also felt that a report in spreadsheet format would be necessary in order to execute the schedule

2.6.8 LSCHEDULER

El-Rayes (2001) developed an object-oriented model for scheduling of repetitive construction projects named LSCHEDULER (Figure 2-11)

LSCHEDULER is implemented as a windows application that supports user-friendly interface, including menus, dialog boxes, and windows. LSCHEDULER can be applied to perform regular scheduling as well as optimized scheduling. In optimized scheduling the model can assist in identifying an optimum crew utilization option for each repetitive activity in the project that provides a minimum duration or cost for the scheduled repetitive construction projects. LSCHEDULER also integrates repetitive and non repetitive activities

The LSCHEDULER model is implemented using C++ programming language that supports object-oriented modeling. The user interface of LSCHEDULER incorporates menus, a tool bar, a status bar, dialog boxes, and multiple document interface windows. To perform scheduling calculations in LSCHEDULER, the user needs to provide necessary input data at the project level and at the activity level including activity relationships

The output data of LSCHEDULER can be for regular scheduling and optimized scheduling. For regular scheduling the output data are in the form of project schedule or cost estimates. Project schedule can be in work days or in calendar dates and can be displayed for repetitive and non-repetitive activities. Project cost estimates provide an estimate of material, labor, equipment, and total cost for each repetitive and non-repetitive activity in the project

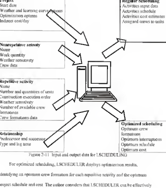

Figure 2-11 Input and output data for LSCHEDULING

For optimized scheduling, LSCHEDULER displays optimization results, identifying an optimum crew formation for each repetitive activity and the optimum project schedule and cost. The author considers that LSCHEDULER can be effectively applied to optimize the scheduling of highway construction projects in order to establish an optimum balance between reducing project duration and its associated additional costs.

2 7 Summary and Conclusions

Not many software are commercially available in order for the user to do planning and scheduling of construction projects using the linear scheduling method. The programs that are available are more a graphical tool than a planning tool Therefore the planners in linear construction projects are mostly using the software that is available on the CPM and bar charts

Research has focused lately on developing software for linear scheduling However, there are some major errors in the programs developed, which if solved will offer a powerful tool for planning and scheduling linear projects

Not taking into consideration the site constraints improper design of time and location axes not considering the productivity rate of activities lack of resource scheduling options, etc are some of the major flaws observed on the software studied

CHAPTER 3
LSM PRINCIPLES AND PROCESSES

3.1 Basic Principles of Linear Scheduling

Transportation projects nowadays have become more complicated than they were in the past Projects are more and more often constructed close to traffic and the public thus increasing the importance of time to construct a project

In general these types of projects involve various professionals who most probably have not worked together before A need is established, a plan is made to satisfy that need and it is eventually presented to a governing body which decides Planners politicians, engineers, contractors, subcontractors and the public are usually involved at various levels during the project This situation requires that the elements of a project are presented in a logical, and in an "as simple as possible" form

If construction projects are to be divided in two distinct categories linear and non-linear projects then transportation projects are definitely within the second category Characteristics such as the small number of repetitive activities moving continuously from one location to the other, flexibility during the construction execution phase the possibility of relocation of construction crew activities to other areas dependency on the production rate and also dependency on resource allocation, need a different approach from the planning and scheduling point of view

Improving scheduling techniques and/or using the most appropriate ones for a specific project is one of the challenges the planners have to deal with in the construction industry This demand comes from the specificity of construction projects. Their dependency on seasons and weather is widely recognized Location is also an important influencing factor which makes apparently similar projects to be actually very different, and to need different approaches both from technological and planning points of view

Tight market also demands better planning if the contractor intends to be a successful one when entering the bidding system and also after starting the job During the construction phase both the owner and the contractor have to deal with project management and control in order to meet the objective of achieving project completion within the contracted terms of duration and cost And last, but not the least for the construction industry well known as plagued by disputes, a proper scheduling technique helps to successfully avoid claims

Linear scheduling (LS) is a way to satisfy the need for simplicity without sacrificing the wealth of information that needs to be presented. Linear scheduling provides the manager with an important tool the ability to visualize a project

Visualizing the flow of work through time and space is very Important Wastage of time due to poor planning and experimenting with, during project execution is thus considerably reduced or even eliminated (Vorster, 1990) Most of the specialists in all fields, admit that it is more efficient and less costly to prevent than to cure

Unfortunately practitioners often forget this aspect because of the speed of the events on site, and the numerous problems they have to deal with They often neglect that a simple graphical tool can help them capture and record their thoughts on paper offering the possibility to build and rebuild the project many times, until the optimum solution has been found

Linear scheduling provides a simple diagram which shows both the location and the time at which a given crew will be performing an operation (Figure 3-1). This graphical technique for scheduling enhances visualization and results in a better understanding of the project (Herbsman, 1987).

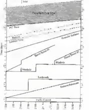

Figure 3-1 Example of Linear Scheduling Graph

In general, progress schedules routinely used in the construction industry relate the start and finish dates of construction operations (e.g. bar chart) and possibly the requisite predecessor and successor operations (e.g. CPM network diagram). These schedules do not relate the specific progress (planned or actual) of the crew(s) for a given operation. The premise behind the use of linear scheduling technique is that, for a linearly oriented construction project, it is not only desirable, but also advantageous to provide this additional information.

Whereas a bar chart schedule uses "time" and "activities" for axes, a linear schedule places construction operations in a graphical chart bounded by axes of "time" and "space".

Linear scheduling makes use of lines to represent linear operations (e.g. milling or paving), bars to represent intermediate, non linear activities (e.g. bridge pier construction) and boxes to represent either periods of planned inactivity (e.g. winter/cold season) or activities that span space over time but not necessarily linearly (e.g. clearing & grubbing a large area over a period of days or weeks).

In addition to allowing on-site personnel as well as managers to readily determine the necessary start and finish dates of operations and the relative sequence of operations, graphical linear scheduling techniques allow project personnel to anticipate the specific location of a crew at a particular time. In addition to being an aid to planning, this feature enables managers to more readily identify delays so that adverse impacts resulting from schedule variances may more readily be minimized.

In the construction process, three general types of work sequences were identified: simultaneous work, successive work, and flow line (Stradal, Cacha, 1982).

Simultaneous work is that which overlays each section available (Figure 3-2). The main advantage of this method is the very short completion time. Disadvantages are the high resource consumption and the fact that sections must be ready for working. The use of simultaneous work is recommended for cases of maximum shortening because of delay, or for "key buildings of works" on which the following activities are dependent.

Figure 3-2 Simultaneous work

Successive work organizes the construction processes in a manner as to complete each section before starting the next one

The main advantage of using this method (Figure 3-3) is meeting the continuity constraints (crews passing successively from a location to the other within the same activity or process) Another advantage is that at a certain moment in time and at a certain location, there is performed a single activity/process

Other advantages that worth mentioning are low resource consumption less need for deposit spaces and site organization

The highest disadvantage is the extremely long completion time The method is recommended where, because of access or technological constraints, the completion of a previous section are necessary before the work starts on the next section

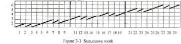

Figure 3-3 Successive work

Flow line tries to combine the advantages of the two previous methods (successive & simultaneous) and also eliminates some of the disadvantages shown before. The method organizes the construction processes in such a manner that each crew has an uninterrupted flow in constant rhythm from section to section. In order to assure the "rhythmical" flow of production, very good management and equal manpower content of all sections for each crew are a necessity.

As with other scheduling methods, the planner/scheduler has some discretion in planning the work. Production rates may vary due to such factors as available resources, crew experience and anticipated weather conditions. The relationships between adjacent operations may vary as well (Figure 3-4) due to safety considerations, work area availability or technological reasons.

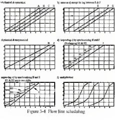

Figure 3-4 Flow line scheduling

3.2 Elements of Linear Scheduling

3.2.1 Activity Duration

In order to comprehend and acquire the ability to use the Linear Scheduling Method (LSM) one must understand its basic elements One basic characteristic of Linear Scheduling which distinguishes it from other project management techniques such as the Critical Path Method (CPM), and the Gantt or Bar Chart, is its inherent ability to instantly provide accurate information on the status of the project in question (Johnston, 1981)

Since the LSM is based upon production rates, it is important that these rates are calculated with accuracy and that they are monitored throughout the duration of the project in order for the manager to ensure the accuracy of the LSM charts (Arditi 1986)

3.2.1.1 The daily production rate method

The daily production rate method is one of the methods that can be used to establish the duration of an activity This method has the advantage of being more flexible and also being based on readily available data from a large variety of sources (Pierce 1988) The formula used for an activity "ij", identified by its starting, and ending moments respectively is

$$\mathbf{T_{ij}} = \frac{\mathbf{Q_{ij} * P_{ij}}}{\mathbf{C_{ij} * Z}} \tag{3-1}$$

Where Tij is the activity duration calculated in working days weeks or months

Qij is the quantity calculated in specific units of measurement (CY, SF, Ton etc)

Pij is the production rate

C_{ij} is the crew size

Z is a dividing factor that depends on the working policy of the company

3.2.1.2 The experience method

The experience method is another way of estimating the duration, which even if not recommended for large and complex activities, is very useful in estimating those kinds of work for which published data is not available (Pierce, 1988). As a matter of fact, the experience of the field personnel is in this case the source of information, and a pretty accurate one too.

In both methods, considering the real conditions of a particular job or site, and adjusting accordingly the calculated times, is a must. Some examples of adjustments that can be done are: rounding up all calculated times, cumulating more types of processes in the activity, adding to the schedule activities that are only time consuming (like drying time), considering the influence of the learning curves when dealing with a series of similar activities, questioning the applicability of the data sources, etc.

3.2.2 Axis Parameters

Linear Scheduling, as mentioned above, provides a tool to supervise the progress of production crews as they move along the linear aspect of the project. To create a linear schedule diagram, the planner must first define the two axes. Currently, due to the minimal use of linear scheduling in transportation projects there is not a consensus on the exact orientation of the axes.

There are two ways of defining the two axes depending on the level of detail desired in the schedule (Bafna, 1991). The first way of axes labeling provides a time vs. length plot of the schedule (Figure 3-5).

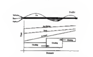

Figure 3-5 Axes labeling time vs distance

The second way of axes labeling (Figure 3-6) provides a length vs time (workday workweek) plot of the schedule Both allow the production rate to be shown as a positive slope line

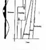

Figure 3-6 Axes labeling distance vs. time

Major and minor labels can be added to both the axes Major labels are for distance and time Minor labels mark the parameters of space and time, and are attached as station numbers on the horizontal axis and the dates on the vertical axes.

Unless linear scheduling becomes more popular in highway construction engineers will use any of the two ways of labeling In addition, the vertical axis may be plotted towards the bottom of the page.

Time scheduling can be in terms of hours, days, weeks or even months The desired level of detail that the project requires decides this. Usually, the day is the most common basic unit for scheduling in construction. As with network analysis, it is preferable to prepare the schedule based upon working days and to convert it to calendar days only at the end (Johnston, 1981). The Linear Schedule diagram can of course be prepared on a calendar day basis with holidays and weekends shown as periods of inactivity. However, such an approach is deemed to constant revision, as lost days due to bad weather, or gained days due to good weather, shift the working days backward and forward on the calendar schedule. In some instances, analysis of a calendar day schedule in short-term planning can benefit the project, if time buffers are significant (Johnston, 1981).

Distance at its turn can be measured in feet or miles, but in highway construction projects, both owners and contractors prefer to measure it in increments of 100-ft stations. As a particularity for high-rise buildings, on the location axis are posed the different levels (ground, level 1, level 2, etc).

3.2.3 Sight Lines

Sight lines are used to represent the work activities with continuous movement. The line is drawn to track movement of a crew through the project as time progresses.

Sight lines are lines that can only be drawn parallel to each axis. Their slope is either equal to zero or one. Usually they are hatched lines drawn on the graph to facilitate in the making of the graph and the monitoring of the activity. Care must be taken in all the steps of producing the graph. One must remember that the graphical result of this procedure must remain simple, and as free from clutter and unimportant lines as possible.

3.2.4 Production Rates

There are two important production rates associated with each activity: a resource production rate and a unit production rate.

3.2.4.1 The resource production rate

The resource production rate for an activity "i" (Pr_{iR_k}) can be defined as the amount of work that can be accomplished by the resource in one time period. The formula to calculate Pr_{iR_k} is

$$Pr_{iR_k} = \frac{Q_{iR_k}}{D_{iR_k}} \tag{3-2}$$

Where: Pr_{iR_k} is the production rate of activity "i" when using resource "k"

Q_{iR_k} is the quantity of work associated with activity "i" when using resource "k"

D_{iR_k} is the duration of activity "i" when using resource "k"

This equation is most often used to estimate the activity duration (D_{iR_k}). The quantity of work (Q_{iR_k}) is usually taken from the plans and specifications, while a standardized production rate for the selected resources and methods (Pr_{iR_k}) is taken from company databases or from any of several construction guides in common use in the construction industry (i.e. R.S. Means)

3.2.4.2 The unit production rate

The unit production rate (Pr_{iU_j}) is characteristic to multi-unit repetitive construction activities and can be defined as the number of repetitive units that can be accomplished by a resource during a unit of time. For an activity "i" performed within any repeating unit "j", Pr_{iU_j} can be calculated with the following formula

$$Pr_{iU_j} = \frac{1}{D_{iU_j}} \tag{3-3}$$

Where Pr_{iU_j} is the production rate of activity "i" performed within unit "j"

D_{iU_j} is the duration of activity "i" necessary to complete unit "j"

Harris and Ioannou (1998) show that the slope of a production line in a Repetitive Scheduling Method diagram is actually given by the unit production rate, and not by the resource production rate. By substituting D_{iU_j} with D_{iR_k} we obtain a directly proportional relationship between unit production rate and activity production rate and an inversely proportional relationship between unit production rate and the quantity of work in the unit.

$$Pr_{iU_j} = \frac{Pr_{iR_k}}{Q_{iR_k}} \tag{3-4}$$

The equation shows that the unit production rate may change from unit to unit as a function of quantity of work while the resource production rate does not.

The quantity of work in activities that repeat from unit to unit is in many cases not the same in every unit. In these instances the unit production rate will vary depending upon the amount of work in each unit. This situation will generate a scheduling chart where each activity has a different slope given by the corresponding production rate.

3.2.5 Access Constraints

The production rate of an activity when updated regularly will provide all the information about that activity such as the start and end times at each phase of construction, expected times of completion, and location of the construction crew. One of the fundamental requirements of linear scheduling is that the production lines are not the fundamental requirements of linear scheduling is that the production lines are not allowed to cross. There is a requirement that a buffer of space, and/or time be maintained between activities. This is done for reasons such as safety, material requirements, concrete curing, and space and equipment availability.

In addition to these constraints, access to a part of the site (location) may not be possible at a certain time interval. In that case, a shaded box will show the limits of access (Figure 3-7).

On a location vs. time LS chart, a vertical line is indicative of an activity that required minimal time. Such an example is the movement of equipment or crews. On the contrary, a horizontal line denotes an absence of productivity during a time interval.

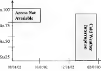

Figure 3-7 Access and weather constraints

In addition to access constraints, there may also be seasonal constraints. Since almost all construction projects take place outside in the elements, there are always chances that at some time of the year, work progress will be hindered or even prohibited by weather.

3 2.6 Activities

The previous paragraphs provided the framework, in which a linear schedule is defined and constructed. The steps that should be followed in order to build a linear schedule graph are

8 First step the manager decides on the orientation and the labeling of the axes

9 Second step buffer guidelines are introduced according to the requirements of the particular project (safety, crew availability, material constraints, etc)

10 Third step the constraints due to weather and site limitations are introduced and accounted for

11 Fourth step the activities may be introduced

From the graphical point of view, activities can be classified in three general types which are shown in Figure 3-8

- Block
- Bar
- Linear

From the dependence point of view two types of activities were also identified (El-Sayegh, 1998)

- Discrete activities
- Continuous activities

The work on discrete activities can not start until the technological requirements are satisfied They don't depend on resource availability

The continuous activities are resource-based Most of the relationships among this type of activities are a start to start relationship with a time lag The work continuity of crews is the basis for the second type of activities

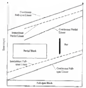
Continuous Full-span Linear
Intermittent Partial Linear
Continuous Partial Linear
Bar
Time (days)
Partial Block
Intermittent Full-span Linear
Continuous Full-span Linear
Full-span Block
Location (distance)

Figure 3-8 Activity types

3.2.7 Lines

Lines are used to track the progress of a crew throughout the whole project. As previously mentioned, the slope of the line is the most important element of this part of the drawing process because it actually shows the production rate (Figure 3-9). A gentle slope signifies a lower productivity rate while a sharper slope marks a higher productivity rate.

Since lines are a basic element of a linear schedule, it is beneficial for the user to define each activity with lines that are distinguished from each other either by thickness, or color or other patterns. Despite the simplicity of the chart, efforts should be undertaken to ensure that the graph is as easy to follow and maintain as possible.

For example, the manager only needs the amount of material to be placed or excavated and the size of the crew that is going to carry out the activity. When a crew moves from one location to another in the same day the graph will show a vertical line

When a crew suspends work at a certain location for any reason, the graph will show a horizontal line at that location.

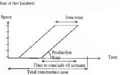

Figure 3-9: Computation of production rhythm

In the actual construction of an activity, the production rate will vary between locations. To account for this variance, the planner leaves some space, or buffer, between activities.

The buffers are introduced in the schedule also in order to account for reasonable amounts of distance to be left between sequential activities. Without the distance buffers activities would occur in very close proximity to each other, or even overlap. This could lead to technological nonsense, or loss of productivity.

3.2.7 Buffers

Buffers can be viewed also as points of intersection between adjacent activities. Because of technological and work safety reasons, two activities cannot occupy the same space at the same time.

Buffers can never be closer than the least time interval, which is defined as the minimum time that has to occur between two adjacent activities at any location in the project as shown in Figure 3-10 (Lutz, Hijazi 1993). The minimum time interval is an equivalent of the activity's float used in CPM

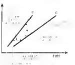

Figure 3-10 Buffer representation

In addition to the least time interval, there is also a least distance interval between two adjacent activities. The distance is measured on the axis other than that of time (depending on the way axes were selected), and it represents the minimum distance allowed between two activities.

The least distance interval will depend on the way location or stations were selected, based on work safety requirements, crew size, and the minimum organizational and technological working area needed for a particular activity.

3.2.8 Bars

In order to show that a crew is working on the same location for a period of time a vertical bar can be used. The line extends to cover the start to finish of that activity. Discrete activities are excellent examples of operations which can be best represented by using bars.

3.2.9 Blocks

Blocks are used to show time and space being occupied, while a crew is performing an activity. Blocks are best used to represent activities that use a large stretch of the length of the project at the same time. In that location, the operation cannot be exactly pinpointed to a specified station location, rather the crew moves around within the whole range of the block.

Blocks can be divided at their turn, in full-span blocks and partial span blocks, depending on whether or not the activity spans the entire location of a project. The continuous or intermittent character of the activity is also considered (Harmelink, Rowings, 1998).

3.2.10 Secondary Symbols and Supplemental Information

In addition to the basic symbols included in the linear schedule (block, bar and line), other symbols (Figure 3-11) or information may be used for added detail (Rahbar, 1991).

In order not to create confusion rather than clarity, the amount of detail used should be adapted to the size and the complexity of the project to be scheduled. The level of detail might vary from project to project and should be tailored to meet the specific needs of those using the schedule.

Multiple schedules of varying detail can be prepared. For example a schedule with minimal detail can provide the owner with a project overview while in order to provide the foreman with sufficient information to prepare for the upcoming week a more detailed schedule should be conceived.

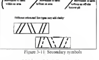
Movement of earth within an area
Movement of earth to/from an area
Movement of earth to/from an off-site borrow pit
Different colors and line types may add clarity

Figure 3-11 Secondary symbols

3.3 Linear Scheduling Algorithm

3.3.1 The Controlling Activity Path

The concept of criticalness is present in linear scheduling as well as in CPM but it has some differences in comparison with the concept of criticalness in networks

The critical path (CP) in CPM establishes the minimum project duration consistent with the technical precedence and resource availability constraints expressed in the network CP is established by adding the durations of the critical activities[1]

In a linear schedule the equivalent of the CP is named "controlling activity path" (CAP), and the sequence of activities that establishes the minimum project duration is named the 'controlling sequence' (Harris, Ioannou, 1998)

Since these concepts form the basis of 'management by exception,' it is important that an LSM algorithm will be equipped with a routine that could single out critical and near critical activities for intense and high-priority management action and floats to allow for flexibility if necessary (Arditi, Tokdemir Suh 2002)

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[1] A critical activity in a CPM network is an activity which if delayed will delay the entire project

In repetitive construction projects identification of critical activities is made differently from CPM Critical activities in a CPM schedule may not coincide with critical activities in an LSM schedule, because in LSM the production rate is the major parameter that determines criticalness, whereas in a network, only activity durations are used for this purpose

The different types of activities that can appear in a linear schedule influence significantly the procedure for determining the controlling activity path.

In this context the linear type of activities should be subdivided depending on whether the activity spans the entire location of the project or not and whether or not the activity is in continuous or intermittent operations The main four subdivisions for an activity are (Harmelink Yamin 2000)

- Continuous full-span linear activities (CFL)
- Intermittent full-span linear activities (IFL)
- Continuous partial-span linear activities (CPL)
- Intermittent partial span linear activities (IPL)

The procedure to determine the CAP in a linear schedule is given in Figure 3-12

3.3.2 Step 1: Determining the Activity Sequence List

Similar to the steps taken in the already familiar CPM, the start in determining the controlling activity path in a linear schedule starts with listing of all project's activities and continues during the same step with the identification of all the possible sequences through these activities

The final output of this step is an activity sequence list The particularity of the activity sequence list is that it does not describe only the order in which activities will occur in the project, but it will also show the location where these activities occur

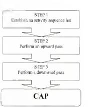


Figure 3-12 Steps in determining the controlling activity path

3.3.3 Step 2: Perform the Upward Pass

The upward pass starts with the beginning of the project and progresses ascendant. During this step the path with the least free time between each pair of continuous full-span activities is identified The origin is the earliest point in time of the origin activity, which will always be a CFL activity The next CFL activity in the sequence list will be the target activity

The relationship between two adjacent CFL activities can be described by three specific elements (Harmelink Yamin 2000) which are illustrated in Figure 3-13

- The least-time interval (LT) which is the shortest time interval between any two consecutive activities
- The coincident duration which represents an interval in time during which two activities that are connected by the least time Interval are both in progress

- The least distance (LD) interval which represents the shortest distance between the two activities that lies within the coincident duration interval and intersects the least-time interval

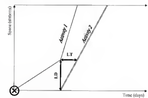


Figure 3-13 Specific elements in linear schedule

All activity types other than CFL will be examined at their turn in respect to the upper and lower bounding CFL activities The segment from the origin up to where the target activity begins is always a potential controlling segment. The controlling activity path will occur in a point located between the time after the origin activity ends and before the target activity begins. Actually the controlling activity path will occur where these two activities are closest to each other, somewhere on the least distance interval

Figure 3-14 shows how to determine the potential controlling segment Figure 3-15 gives an example of the way the upwards pass is performed in a project containing six (A to F) CFL activities (Rowings Harmelink, 1995)

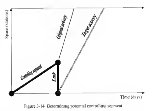


Figure 3-14 Determining potential controlling segment

The process starts with the pair of activities AB for which LT and LD are determined. Then the potential controlling segment and the potential critical link are also determined. The process repeats for each pair of following CFL activities: BC, CD, DE, and EF.

It can be noticed that there are portions of a linear activity which are not controlling segments. This aspect is entirely different from the critical path in network scheduling where an activity is either entirely critical or not. In linear scheduling we can encounter different combinations of controlling and non-controlling segments during the development of a single activity.

3.3.4 Step 3: Perform the Downward Pass

The backward pass is performed in order to identify the segments of activities for which the production rate cannot decrease without extending the duration of the construction project. The start for the backward pass will be the end of the last CFL activity of the project.

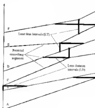

F
Least time intervals (LT)
E
Potential controlling segments
D
Least distance intervals (LD)
C
B
A
Time (days)
Location (stations)

Figure 3-15. Upward pass

Figure 3-16 shows a backward pass for the same project characterized by six CFL activities. The end of the last activity (activity F) is the starting point. Activity F will be followed back in time until the potential controlling link with the previous activity (activity E) is reached. The segment that unites these two points is a controlling segment.

The potential controlling link becomes now a controlling link showing the point in time where the controlling activity path changes from an activity to another. The process will be repeated by moving downward through the linear schedule until we reach the starting point of the project.

The final output of the downward pass is the control path activity (CAP)

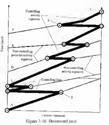

Controlling activity segments
1
2
3
F
E
D
C
A
Time (days)
Non-controlling potential activity segments
Non-controlling activity segments
Controlling link
Location (stations)

Figure 3-16 Downward pass

3.3.5 Rate Float

One of the important information also offered by LSM is the rate float of an activity which marks the difference between the planned production rate of the activity and the lowest possible production rate

The lowest possible production rate of an activity A that is characterized by a starting point S_A defined by the coordinates (X_{S_A}, Y_{S_A}) and an end point E_A defined by the coordinates (X_{E_A}, Y_{E_A}) is

$$\text{Lowest possible production rate} = \frac{X_{E_A} - X_{S_A}}{Y_{E_A} - Y_{S_A}} \tag{3-5}$$

In equation 3 5 (X_{S_A}, Y_{S_A}) are the coordinates of the new earliest start time of activity A

The rate float of activity A will be.

$$\text{Rate float} = \frac{X_{E_A} - X_{B_A}}{Y_{E_A} - Y_{B_A}} - \frac{X_{E_A} - X_{S_A}}{Y_{E_A} - Y_{B_A}} \qquad (3.6)$$

3.4 Summary and Conclusions

LSM is a simple and easy to apply scheduling methodology. In contrast to other scheduling techniques, like CPM network, an LSM schedule is presented graphically as an X-Y plot, where one axis represents location and the other the time. Lines, bars and blocks are the main visual representations of activities used in LSM, but other additional symbols can also be used.

The principles and concepts of LSM have many similarities to the concepts and relationships used in CPM precedence networks. The CPM concept of "critical path" has an equivalent in LSM called the "controlling activity path". The difference between the two concepts comes from the fact that in LSM the major parameter that determines criticalness is the activity production rate, while in CPM criticalness is given only by the activity durations.

CHAPTER 4
UNCERTAINTY IN CONSTRUCTION SCHEDULING

4.1 The Concepts of Risk and Uncertainty

4.1.1 The Concept of Risk

The concept of risk is frequently used to assess and evaluate uncertainties associated with an event (Bender 2000) Despite the fact that there is a vast literature dedicated to the analysis of risks in different industrial fields, the term can still be somewhat ambiguous if it is not clearly defined from the beginning.

The AACE International's risk management dictionary developed by the Risk Management Committee in an effort to provide standard terms for publications and presentations defines risk as follows:

> Risk is an ambiguous term that can mean any of the following: all uncertainty (threats and opportunities) or downside uncertainty (only threats) or the net impact or effect of uncertainty (threats or opportunities).

A common way to measure risk is to match the probability of occurrence of an event $P(E)$ with the expected outcomes associated with the event's occurrence $O(E)$. The result is a pair $[P(E),O(E)]$ for each event E.

The risk involving multiple events E_k, $k = 1, 2, \ldots n$ can be represented by the equation $Risk = \{[P(E_1),O(E_1)],[P(E_2),O(E_2)],\ldots[P(E_k),O(E_k)],\ldots[P(E_n),O(E_n)]\}$

The outcomes of a risk event may have either positive or negative consequences. A significant way to quantify these consequences in a construction project is to measure the dollar amount (lost or gained), number of days (delayed or accelerated) or number of fatalities

4.1.2 Risk Management

The management of risk consists of the following main components (Risk Management Committee, 1995) risk assessment, risk analysis, risk mitigation , and risk control as shown in Figure 4-1

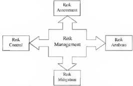


Figure 4-1 Components of risk management

4.1.3 Risk Assessment

Risk assessment is the process of identification of risks and uncertainties that may affect a project Data obtained through the risk assessment phase will be used during the risk analysis phase and will establish the foundation on which the entire risk management process will be developed

The identification of risks and uncertainties can be made by using either quantitative or qualitative methods Quantitative risk assessment methods rely on statistical methods and databases Qualitative risk assessment methods use expert opinions to evaluate the probability and consequence of a hazard interaction with the system (Bender, 2000)

4.1.4 Risk Analysis

Risk analysis represents the systematic process during which the probability of occurrence of each risk is quantified and the potential severity of each risk's impact on the project is computed. The impact may be a range of values or may take the form of a probability distribution

As the phase of risk analysis uses the data gathered through risk assessment, the techniques to be used can be classified at their turn into quantitative risk analysis techniques and qualitative risk analysis techniques. In Table 4-6 a list of the main quantitative and qualitative risk analysis techniques is presented (del Caño de la Cruz, 2002)

In addition to the techniques listed in Table 4-1 there are other support tools like interviewing, brainstorming and the Delphy method that can also be used to quantify the probability of occurrence of risk when performing a risk analysis for a project.

Table 4-1 Risk analysis techniques

Quantitative risk analysis techniques	Qualitative risk analysis techniques
• Sensitivity analysis	• Checklists
• Expected value tables	• Assumptions analysis
• Triple estimates and probability sums	• Data precision ranking
• Monte Carlo Latin hypercube simulation	• Probability and impact description
	• Probability impact risk rating tables
• Decision trees	• Case/effect diagrams
• Probabilistic influence diagrams	• Flowcharts and influence diagrams
• Multicriteria decision-making support methods	• Event and fault trees
• Process simulation	
• System dynamics	
• Fuzzy logic	

4.1.5 Risk Mitigation

Risk mitigation is the process of documenting the results of the risk analysis. The final product of risk mitigation is a risk management plan that will contain predefined action steps to be executed in order to eliminate or reduce the probability of occurrence and also the impact of threats. The risk management plan also will also consider the positive aspects of risk, by providing the action steps to be taken in order to increase the impact of any occurring opportunity.

4.1.6 Risk control

Risk control is the last phase of risk management and represents the process of implementation of the risk plan.

4.1.7 Risk – Uncertainty Correlation

If risk was defined as the net effect or impact of uncertainty, the same Risk Management Committee defined uncertainty as

> The total range of events that may happen and produce risks (including both threats and opportunities) affecting a project. Uncertainty = Threats + Opportunities

Opportunities are the potentially positive uncertain events that could improve the probability that a certain desired outcome will happen, while threats are uncertain events that have a potentially negative result or reduce the probability that a desired outcome will happen.

Uncertainty is inherent to any project and stays at the origin of risk. There are risks with a single (normal) uncertainty like the weather phenomena and there are risks with other components of uncertainty that have an interactive nature (del Caño de la Cruz, 2002). Social, political, and economic phenomena are examples of interactive uncertainties.

4.2 Various Approaches to Uncertainty

4.2.1 A Cognitive Approach to Uncertainty

Uncertainty arises from a lack of information about the state of the world that makes it impossible to determine if certain statements are true or false (Parsons 1996)

From a cognitive perspective uncertainty can be found at the third level of the pyramid of ignorance hierarchy as shown in Figure 4-2 (Ayyub 2001). Each element of the pyramid is defined and described in Appendix B, based on Webster's dictionary and Ayyub's classification of elements of ignorance

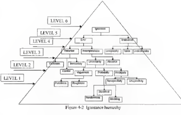


Figure 4-2 Ignorance hierarchy

Over the years there have been many attempts to produce a categorical classification of different types of uncertainty, and to elucidate the relationships between them (Parsons 1996)

4.2.2 Levels of Uncertainty

In analyzing the strategies in assessing uncertainty, Courtney, Kirkland and Viguerie introduce the concept of residual uncertainty and define it as being the uncertainty that remains after the best possible analysis had been performed. They also ascertain four broad levels for residual uncertainty which are described in Table 4-2 (adapted from Courtney, Kirkland, Viguerie 1997).

Table 4-2 Levels of uncertainty

Level No	Uncertainty	Future	Outcomes	Appearance
1	Clear enough	Single forecast	Sufficiently precise	
2	Alternate	A few discrete scenarios	Discrete and clear. Hard to predict.	
3	Range	A range of future	Outcome may be anywhere within the range	
4	True ambiguity	Limitless range	Impossible to identify the range of potential outcomes	

4.2.3 Types of Uncertainty

There are many sources for uncertainty and there are also many types of uncertainty. The main types of uncertainty mentioned by Balon and Price include error, imprecision, variability, vagueness, ambiguity and ignorance. At his turn Ayyub considers that specifically in engineering, uncertainties can be attributed mainly to ambiguity, likelihood, approximations and inconsistency (Ayyub 2001).

The diversity in terms for different types of uncertainty makes the scheduling process a very difficult task because the information concerning each specific uncertainty is scarce (Balos and Price, 2003). Several formal techniques for managing the different types of uncertainty have been developed but there has not been any consensus on the appropriateness of such techniques so far. It seems that there is no best theory of uncertainty and therefore the choice of the most appropriate technique depends upon the specific problem.

4.2.3.1 Ambiguity

Ambiguity is generally due to a non cognitive root causes. Ambiguity is a state in which an expression or word may have a number of distinct meanings and only the context may help clarifying the real meaning.

An example of ambiguity in natural language is the following statement: In December the weather will be unfavorable for the earthworks. It is obvious that this qualitative description can be understood variedly. The risk factor "unfavorable weather' does not have an exact meaning, because the qualifier "unfavorable" may assume several degrees of intensity. Unfavorable weather may involve a wide spectrum of human perceptions, as there is no rigorous definition of what unfavorable weather is.

Ambiguity in an engineering system comes from either not fully identifying possible outcomes or incorrectly identifying possible outcomes (Ayyub, 2001).

4.2.3.2 Vagueness

Vagueness arises when the outcome of an experiment can not be properly observed. A vague expression is ill defined and lacks preciseness or sharpness. Vagueness is inherent in the case of photographic and other visual representations.

An example of vagueness in engineering is when presumably some subjects are asked to interpret a drawing or to judge the degree of damage in a construction work from photographs. The subjects may give vague responses depending on the clarity of the drawings or the photographs.

The vagueness related uncertainty is due to cognitive sources (Ayyub, 2000) that include the following:

- The way certain parameters were defined, e.g., project performance, quality, skill and experience of construction workers and engineers, environmental impact of projects, etc.
- Other human factors
- The way the correlations and dependences among the parameters of the problems are modeled and interpreted, especially for complex systems
- Other sources like conflict in information, and human errors and organizational errors

4.2.3.3 Fuzziness

Fuzziness is a particular type of vagueness characterized by a gradual transition from a membership state of an element to a set. Fuzziness is most frequent in processes like reasoning, learning and decision-making, where human judgement is essential.

In general, a measure of fuzziness is a function $f: \widetilde{P}(X) \rightarrow R^{+}$ where $\widetilde{P}(X)$ denotes the set of all fuzzy subsets of the fuzzy power set X (Klir, Wierman 1998).

4.3 Methods for Assessing Uncertainty

4.3.1 Approaches for Handling Uncertainty

Assessing uncertainty is done in most cases by attaching a numerical value to an element. The numerical value represents a subjective measure of the certainty of the uncertain element, as suggested by the observer. The way in which the numerical value is manipulated depends on the theory that underlines the number.

4.3 Methods for Assessing Uncertainty

4.3.1 Approaches for Handling Uncertainty

Assessing uncertainty is done in most cases by attaching a numerical value to an element. The numerical value represents a subjective measure of the certainty of the uncertain element, as suggested by the observer. The way in which the numerical value is manipulated depends on the theory that underlines the number.

Researchers produced different classifications for the methods used to characterize, evaluate and quantify uncertainty depending on the type of uncertainty (Table 4-3).

Table 4-3. Approaches for handling uncertainty

Uncertainty Theory	Researcher(s)	Year
• Probability Theory • Certainty Factor Theory • Dempster Shafer Theory • Fuzzy Set Theory	Baloi and Price	2003
• Basic Statistic Theory • Stochastic Simulation • Monte Carlo Simulation • Fuzzy Set Theory	Hoogeweg	1999
• Classical Set Theory • Fuzzy Set Theory • Possibility Theory • Evidence Theory • Probability Theory • Fuzzified Evidence Theory	Klir	1994

The methods most often used in assessing uncertainty in construction projects are detailed in the following paragraphs. The characteristics of these methods are analyzed and their shortcomings are also described focusing on their effectiveness in dealing with ambiguities and vagueness.

4.3.2 Basic Statistical Methods

Basic statistical methods usually involve estimating and calculating the mean, variance, and confidence intervals of the observed population.

- The probability P(E) of the event (E) which describes the uncertainty about the outcome of the event.

These methods work well for static data, but the construction environment is dynamic and variables change over time. Probability theory considers all uncertainty random, though, not all types of uncertainty are random. A great deal of management issues in construction are mainly cognitive and do not comply with randomness properties. Many of these issues do not lend themselves to precise measurement.

Several authors have highlighted some serious shortcomings related to the Bayesian statistics. Any exceptional circumstance, (named "temporary disturbance" or 'volatility"), will feed into statistics averages and can take entire time series into a wrong direction, making forecasting inaccurate (Hoogeweg, 1999).

There is a type of uncertainty known as statistical uncertainty which arises from sparse data on the system variables. In order to precisely characterize the system variables with the proper probability distribution functions they need to be very well known and understood. Analysts typically use whatever data is available to make predictions of the distribution parameters (e.g. mean and standard deviations) for these variables (Mahadevan, Smith. 2003). These predictions at their turn have a degree of uncertainty, which can be quantified if the parameters themselves are treated as random variables.

For example, if a missile length is a system variable with inherent variability, it may be represented by a distribution with a specific mean, μ_{length} and standard deviation, σ_{length}. To the extent that μ_{length} and σ_{length} are uncertain, they may have their own random distribution parameters, μ_μ, σ_μ, μ_σ, and σ_σ. In this case, the system failure probability will also be a random variable and confidence bounds may be used to articulate the uncertainty in this calculation.

Statistical uncertainty arises only from a lack of data regarding the system variables. In order to reduce statistical uncertainty additional testing is needed in order to obtain a better understanding of the randomness in system variables.

4.3.3 Stochastic Simulations

Stochastic simulations need fewer data but require a model that is capable to describe the process. A stochastic simulation model has one or more random variables as inputs which lead to random outputs. Since outputs are random, they can be considered only as statistical estimates of the true characteristics of the model.

The difficulty in using stochastic simulation is that it requires a large number of iterations of the recursive formula. Since decision variables are not quantitative stochastic approximation methods are not fully applicable. The most frequent approach to solving decision making problems has been complete enumeration or random sampling.

Complete enumeration is possible only if the number of configurations for the system is small. However, even for a fairly small problem such as a production system with 4 stations, 3 activities, 3 routing policies for each station, and 4 different crews, 144 different situation models might need to be built for a complete enumeration.

Stochastic scheduling at its turn is concerned with scheduling problems in which the processing times of tasks are modeled as random variables. The job's processing time is considered not to be known until is complete. Schedule in this case might be preemptive or non-preemptive, it might occur on one only or on many processors

A typical result in the area of stochastic scheduling is that if n jobs are to be processed on m identical machines operating in parallel then the longest expected processing time first minimizes the expected time at which all jobs are complete.

4.3 4 Monte Carlo Simulation

Monte Carlo simulations are by far the most popular method for addressing uncertainty in assessments

Monte Carlo simulation uses probability distributions, primarily beta distributions, to represent the variable, for example activity duration Beta distributions can be defined with three values for each input. the most likely value, the pessimistic, the optimistic Random numbers are used to extract one duration estimate from each activity duration distribution resulting in one completed project run Multiple runs are made, and the project duration from each run is combined to define a probability distribution function for the project outcome

A common problem though not recognized by most users, is that many researchers apply Monte Carlo simulations to account for variability in the input data and at the same time equate this to accounting for uncertainty This application by itself does not account for uncertainty, as the uncertainty is hidden in the imprecision of the data (Hoogeweg 1999)

A typical example of inappropriateness of using Monte Carlo simulation is when considering the weather impact (rain particularly) or weather uncertainties in project scheduling Because the amount of rain differs according to the location and season, assuming a certain distribution and frequency of rain in order to use Monte Carlo simulation seems to be inappropriate

4.3.5 Fuzzy Set Theory

Fuzzy theory emerged in the second half of the 20th century by challenging basic assumptions of three classical theories (Klir, 1991) the assumption of sharp boundaries in classical set theory, the assumption of classical (Aristotelian) logic that each proposition must either be true or false and the assumption of additivity in classical measure theory and, in particular probability theory

During the process of forecasting experts usually make use of linguistic values of fuzzy nature in order to describe the future events For example linguistic variables like "possible", "unlikely", "highly probable" or "certain" can be used to describe project duration These terms are fuzzy sets which represent the primary imprecision that is associated with the structure of the concept (project duration for example)

The fuzzy set theory is the only mathematical tool that can process linguistic terms as used by experts (Table 4-4) allowing the quantification of expert knowledge in estimating and assessing uncertainty (Cho Choi, Kim 2002)

Table 4-4 Criteria for uncertainty degree

Uncertainty degree of [illegible]	Uncertainty degree of Experience [illegible]	Uncertainty degree of [illegible]	Uncertainty degree of [illegible] analysis	Determining uncertainty range
Very Small	Very Small	Very Small	Very Small	Very Very Close
Very Small	Small	Very Small	Small	
Small	Very Small	Small	Very Small	
Very Small	Fair	Very Small	Fair	Very Close
Fair	Very Small	Fair	Very Small	
Small	Small	Small	Small	
Small	Fair	Small	Fair	Close
Fair	Small	Fair	Small	
Very Small	Large	Very Small	Large	
Large	Very Small	Large	Very Small	
Fair	Fair	Fair	Fair	Fairly Close
Small	Large	Small	Large	
Large	Small	Large	Small	
Fair	Large	Fair	Large	Fairly Fairly Close
Large	Fair	Large	Fair	
Large	Large	Large	Large	

Fuzzy set theory started to find application in construction scheduling since 1979 as shown in Table 4-5 (adapted from Gurffinda, Nagi, 1998) by being progressively used as an alternative to statistical modeling

One of the main benefits of fuzzy logic is that it allows users to use their own terminology. Fuzzy models take an intermediate place between numerical and symbolic models. However, its application to particular types of construction projects like the multiple repetitive construction projects has yet to be researched.

In this research the fuzzy approach will be utilized to propose an efficient and systematic uncertainty assessment.

Table 4-5 Research history in fuzzy project scheduling

Scheduling Method	Novel Attributes	Author	Year
Fuzzy PERT	8 activity network for selling and producing a television commercial	Shipley et al	1996
	Compares fuzzy network and PERT over four basic network configurations of 4 to 8 activities	McCahon	1993
	Discrete and continuous possibility distributions	Buckley	1989
	Compares stochastic PERT and fuzzy PERT	Lootsma	1989
	Triangular activity times	McCahon and Lee	1988
	Tutorial on fuzzy PERT	Dubois and Prade	1985
	11 activity 9 node network	Chanas and Kamburowski	1981
	17 node network model for scheduling academic programs	Prade	1979
Fuzzy CPM	Fuzzy resource constrained project scheduling	Lorterapong	1994
	Studies fuzzy slack	Nasution (1994)	1994
	Project crashing formulation	DePorter and Ellis	1990
	Tutorial on fuzzy CPM	Kaufmann and Gupta	1988
Solution Procedure for Fuzzy Projects	Uses fuzzy Delphi method and combines composite and comparison methods	Chang et al	1995
Fuzzy Project Scheduling Support	Fuzzy project 53 activity network for scheduling support resource allocation in system software development	Hapke et al	1994

The output of a fuzzy model is more semantic rather than quantitative because of the very high level of abstraction of the model. Fuzzy rules express a broad state space relationship between the antecedent and the consequent of a rule, resulting in a wide and dynamic range of possible states For example the single rule, "IF height is *tall* THEN weight is *heavy* takes the place of many different rules that would specify a possible weight value for a number of bracketed height values

4.3 6 Fuzzy Sets versus Probability

Semantically the distinction between fuzzy logic and probability theory has to do with the difference between the notions of probability and the degree of membership (Kantrowitz, Horstkotte, Joslyn, 1994)

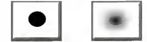
Probability statements are about the likelihoods of outcomes an event either occurs or does not occur With fuzziness, one cannot say clearly whether an event did or did not occur instead fuzziness tries to model the extent to which an event occurred

There are many similarities between fuzziness and probability One of the largest similarity but superficial and misleading is that both systems quantify uncertainty with numbers in the unit interval [0 1] This literally means that both systems describe and quantify the uncertainty numerically The structural similarity is that both systems algebraically manipulate sets and propositions associatively, commutatively, and distributively Those similarities are misleading because a key distinction comes from what the two systems are trying to model (Kosko, Prade 1995).

Uncertainty is a more particular notion in comparison with the notion on truth. Degrees of uncertainty can be attached to a non-fuzzy proposition in order to model the fact that it is not known whether a proposition is true or false. Uncertainty is at the meta-level with respect to truth and is related to practical situations where information is missing or is contradictory (Dubois, Prade, 1997) In classical logic truth is binary (true or false) while uncertainty is ternary (surely true, surely false, or unknown)

Fuzzy set theory assumes that in addition to full membership and non-membership of an object in a given set, various degrees of membership are also possible. A usual notation assigns the value 1 to full membership 0 to non-membership and values between 0 and 1 to partial degrees of membership In probability theory, truth is usually binary (crisp propositions) while uncertainty takes on all values in the unit interval

In conclusion, instead of the black and-white world of probability, the world of fuzzy sets consists of various shades of grey (Nikaneo, 2003) as shown in Figure 4-3



Conventional set

Fuzzy set

Figure 4-3 Conventional set versus fuzzy set

Both from theoretical and practical points of view, fuzzy sets and probability are considered to be contrasting instruments to be used in addressing uncertainty (Dubois, Prade, 1997) On the other hand, as uncertainty highly depends on the way a system manifests itself and also on the method used by the observer to properly capture the real world's system way of manifesting, it seems that none of the instruments used to manage uncertainty is general enough

One of the advantages of using fuzzy numbers over probabilistic models for the processing times is that the makespan[2] will be a function of fuzzy numbers as well Therefore the makespan can be computed very efficiently through interval arithmetic at various α - levels and the objective can be also computed at it's turn through one dimensional integral (Balasubramanian, Grossmann, 2003)

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[2] The makespan is defined as the time span between the start and the end of the project.

If the treatment of processing time uncertainties in production scheduling problems is made by using probabilistic models that describe the uncertain parameters in terms of probability distributions the distribution of the makespan has to be obtained through several parametric multiple integrals which is very difficult to obtain (Balasubramanian Grossmann, 2003)

Minimization of the total project duration is one of the main objectives in project scheduling and is also a common performance measure (Kolish, Padman 2001) According to this performance measure if two schedules which differ only in the finish time of one activity are compared, the schedule which has the smallest finish time for that activity is considered to be at least as good as the other schedule

In conclusion fuzziness differs from probability by the type of information possessed The fuzzy memberships quantify similarities of objects to imprecisely defined properties while probabilities provide information on expectations over a large number of experiments.

4.3.7 Probability versus Possibility

Possibility theory is a new form of information theory which is related to but independent of both fuzzy sets and probability theory

Possibility is the degree of ease with which an event may occur Reducing the possibility of an event normally reduces its probability Probability is the degree to which a proposition may be true or false Reducing probability does not reduce possibility

In conclusion possibility shows whether an event can happen while probability shows whether it will happen (Godfrey, 2003).

Technically a possibility distribution is a normal fuzzy set (at least one membership grade equals 1). For example, all fuzzy numbers are possibility distributions However possibility theory can also be derived without reference to fuzzy sets

The rules of possibility theory are quite similar to the rules of probability theory The difference between these two theories consists in the fact that while the probability theory uses PLUS/TIMES calculus, the possibility theory uses either MAX/MIN or MAX/TIMES calculus, which offers a methodological advantage of the possibility theory over the probability theory The advantage arises from the fact that the PLUS/TIMES calculus of probability theory does not validly generalize nondeterministic processes while MAX/MIN and MAX/TIMES do (Kantrowitz, Horstkotte Joslyn, 1993).

Also, the possibility theory has a way of measuring information which is similar to the stochastic entropy This particular measure is called nonspecificity

4.3.8 Advantages of Fuzzy Models

According to Cox (Cox, 2002), fuzzy models have the following advantages in comparison to other simulation methods.

- Are much more compact
- Encode a higher degree of knowledge
- Usually execute faster
- Are less prone to error
- Work well with missing decision points
- Can be maintained much more easily

This means

- Less experienced knowledge engineers can build more complex models (very good for engineering)

- Less time is needed to extract intelligence from experts (whose time is generally very valuable)
- Less time is required to design and prototype the model
- Less time is required to find and repair errors
- Less time is used to code and extend capabilities
- Less time is needed to verify and fine tune the model

There is less difference between the way an expert expresses a problem and its solution and the way it is encoded in the expert/decision support system (this is usually referred to as cognitive dissonance)

The benefits of fuzzy models mean, in general, that more models can be maintained with a smaller high technology staff more extensive capabilities exist for improving model performance, better more natural knowledge representations are available an enhanced capability exists for encoding common sense into the model and a better visual understanding of the model properties is usually available.

4 4 Uncertainty in Scheduling Construction Projects

4.4.1 Introduction

Due to their unique and extremely complex nature, construction projects are highly sensitive to both internal and external factors that inherently build-in uncertainties into the project, which can have a significant effect on the outcome of the project

Along with the budget the construction schedule is one of the two main factors used to measure control and evaluate the performances of the construction projects

Most schedules are developed in a deterministic manner by assuming that the activity durations are known with some certainty In most construction schedules the durations are given as a single most likely numerical value

In order to address uncertainty in construction projects the Program Evaluation and Review Technique (PERT) can be used where the estimator has to define a statistical distribution for each activity that represents its possible duration in the light of the uncertainty in the project

Because sufficient data are rarely available for analysis to define a distribution with complex parameters the most often used distributions for the activity durations are the beta and triangular distributions (Nasir, McCabe, Hartono, 2003). These values are usually based on expert opinion taking into consideration the perceived risks associated with the expected project conditions

4.4.2 Sources of risk in construction

Construction projects are exposed to a wide variety of risks. Any construction risk analysis should start by identifying and addressing each source or characteristic of risk.

A list of the most common sources of construction risks and their possible causes or uncertainties is given in Table 4-6 (Bender, 2000). These different sources of risk can have either a positive or negative impact both on the performance of the construction project. The three most important risk consequences that project management is concerned with are

- Cost
- Schedule
- Technical performance

Other consequences such as safety, client's un-satisfaction, loss of goodwill or reputation, quality, and environmental effects are also in the management's focus. These consequences could result in costs or gains if not on the current project, then on future projects.

Table 4-6. Sources of risk in construction projects

Source of Risk	Causes/Uncertainties
Cost	Uncertain cost estimate based on historical data
Schedule	Schedule based on past and predicted performance
Labor Problems	Uncertain skills Productivity uncertainty
Project Management Issues	Experience level Relationship inside teams Relationship with subcontractors
Safety Problems	Accident potential
Excessive Change Orders	Potential for changes
Unforeseen Conditions	Undefined underground Hidden site conditions
Environmental Concerns	Regulatory approvals Mitigation of environmental concerns
Equipment Issues	Selection of equipment Selection of techniques Potential for equipment failure
Inflation	Material and labor price increases
Weather	Act of God
Complexity	Unforeseen level of difficulty
Client or Owner Initiated	Potential owner's representatives, architects, engineers and inspectors are overly critical or difficult to work with
Fire	Fire hazard from work operations, vandalism or lightning
Suppliers	Non-performance from vendors, subcontractors or suppliers
Property Loss	Theft Sabotage Vandalism
Design	Incomplete or lacking design
Quality	Poor quality Poor technical performance
Political	Loss of political support

4.4.3 Factors That Influence Construction Duration

Construction duration is the main output of scheduling. But duration can be viewed from a large diversity of perspectives which might create discrepancy in the identification of factors that affect either planned or achieved construction duration.

A list of factors that affect construction time is given by Nkado. The rank of the factors identified by Nkado is shown in Table 4-7 (Nkado, 1995)

Table 4-7 Factors affecting construction time

Factors	Mean rank (29 cases)
Ease of communication	23.23
Possible changes to initial design	22.50
Regulations	22.22
Category of client	19.83
Weather	18.48
Use of standard forms	17.16
Previous working relationship with team	16.93
Statutory undertakers	16.21
Previous working relationship with client	16.14
Previous experience on project	15.72
Previous performance of site management	15.24
Financial ability	15.07
Proportion of main vs subcontractors work	14.93
Suitability to project type	14.70
Size of project	14.59
Level of resource deployment	14.24
Incorporation of special plant in building	13.72
Function end use	12.36
Buildability of design	11.38
Project information	11.26
Complexity	11.19
Availability of suitable management team	10.69
Priority client gives on construction time	10.53
Form of construction	10.48
Location	10.24
Specified sequence of completion	9.74
Priority the design team gives on construction time	9.36
Programming of construction work by contractor	7.81

Nkado further combined the factors into six main categories:

- client
- design and specialist consultants
- contract
- project
- site management
- external influences

4.4.4 Factors Considered in Scheduling Construction Works

Estimating a construction project duration that will reflect as close as possible the real development of a project is one of the main challenges in scheduling

A significant example of different approaches in scheduling and estimating project/contract durations was at the DOT scheduling engineers meeting in Tallahassee[2] For this meeting the schedulers from each district presented their estimations of the contract time for 3 different projects Table 4-8 shows the outcome for each project and each district

Table 4-8 Variations in contract time estimations

Project ID	Districts							
	D-1	D-2	D-3	D-4	D-5	D-6	D-7	D-8
2186681-52-01	350	N/A	300	270	200	240	150	250
4057561-52-01	310	N/A	365	560	345	610	400	360
2280721-52-01	320	N/A	224	315	225	270	240	N/A

For project 218668 the project time ranged from 150 days to 350 days with 3 of the seven districts being in the 240-270 day range District 7 which had the lowest estimated duration explained that they used the critical path method using a 5 day work week, and they also considered some factors as a low production rate of 55 for the milling and resurfacing They also combined some of the work simultaneously, such as the bridgework

District 3 actually compressed their days to 250 by readdressing the work items This district also had some insights to this project due to the fact it was constructed in their district. Basically all districts used the same production rates as described in the "Guidelines for Establishing Contract Duration " Actual Contract days were 240

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[2] http //www dot state fl us/construction/CONSTADM/Meeting_Minutes/Scheduling_Meetings.htm. 8/21/2003

For project 405756 estimated durations ranged from 310 days to 610 days with 3 of the seven districts being in the 345-360 day range Actual contract time on this project was set at 348 days This project was also calculated using a 5 day work schedule There were some unknowns involved in the calculation of days such as the drilling for threaded rods to the columns, grouting the post-tension rods.

Trying to calculate time for this type of work was difficult to set There seemed to be a different total number of columns interpreted from the plan set by some possibly misinterpreting the plans This project was a District Bridge contract and there was some work items that were not related to the guidelines for establishing contract duration District 7 commented that basically the difference in time was due to the different components of work being performed

For project 228072 estimated durations ranged from 224 days to 320 days with 4 of the seven districts being in the 224-270 day range The actual contract time on this project was set at 320 days This project was calculated using a 5 day work schedule District 1 calculated their time by using the start to finish time Some items of work were controlled by the predecessor/successor and their relation to each other

This project was calculated to 320 days by dividing into 3 phases for the separate areas of work to be performed, as did districts 6 and 7 District 3 divided their time into 6 phases of controlling work and district 4 and 5 only one phase. District 5 and 7 had the signalization and lighting work being performed the same time as other work was being performed.

The conclusion of the previous example is that even if schedulers are provided the same amount of information there will be a wide range of duration estimations.

depending on the schedulers' experience and their approach to the project The question that arises is What are the most important factors that should be considered during the process of developing a schedule?

In a research done by Birell forty-four factors were identified as being worthy of consideration by the scheduler in creating a good construction schedule (Birell, 1998) These factors are classified by their relative importance into most important medium important, and lesser important (Table 4-9)

Table 4-9 Scheduling factors

The Relative Importance of Scheduling Factors		
Most Important	Medium Important	Lesser Important
• Optimum completion date • Lead time for material delivery • Type of construction • Critical items • Work or material by others • Previous experience of the contractor • Complexity of the project • Previous experience of the scheduler • Subcontractor input • Contract, drawings and specs • Restraining items (work and materials) • Expected productivity • Size of the project • Communication with others • Conditions which affect productivity	• Availability of materials • Anticipated problems • Owners requirements • Flexibility of the schedule • Availability of workers • Balance between manpower loading and equipment capacity • Scheduling experience of the superintendent • Ease of updating • Maintenance of a consistent workforce • The estimate • Weather • Availability of high skilled workers • Availability of construction equipment • Placement of equipment on the site • Interference from utilities • Optimum movement of crews during construction • Location • Traffic patterns around the site • Contractors company image • Job safety	• Cleanliness of the workplace • Scheduling experience of the A/E • Scheduling experience of the owner • Possible claims and lawsuits • Type of neighborhood • Specific billing requirements • Cash flow • Craft jurisdiction • Prevailing winds

4.4.5 Construction Delays in Construction

Construction projects often finish late in terms of contract dates, programmed duration's and consequently client/user expectations. Disappointment, disputes and litigation frequently follow in many cases it is the expectations which are established that are unrealistic

In highway construction the contract time for performance as determined by the State Highway Agency (SHA) might have been incorrectly calculated from the start (Thomas, Ellis, 2001). The consequence will be delays in construction which will lead to construction time extensions, having an unfavorable impact on the user which in this case is the motoring public and community

The root causes of time delays in transportation construction projects are presented in Table 4-10 (Thomas Ellis 2001).

Table 4-10 Most frequent reasons for delay in highway construction

	Survey of Highway Contractors		Survey of SHA's
1	Utility relocations delayed	1	Utility relocations delayed
2	Errors in the plans or specifications	2.	Differing site conditions (utility conflicts)
3	Differing site conditions (utility conflicts)	3	Errors in the plans or specifications
4	Weather	4	Weather
5	Owner requested changes	5	Permitting issues
6	Site conditions (other than utilities)	6	Differing delays in right of way acquisition
7	Permitting issues	7	Delays in environmental planning
8	Delays in environmental planning	8	Insufficient work effort by contractor
9	Delays in design	9	Differing site conditions (others)
10	Pay items do not match scope of work	10	Poor coordination of work by contractor

A study done by the Federal Highway Administration (FHWA) also found that the most common reasons for projects delays are

- Lack of funding or low priority (32 %)

- Local controversy (16 %)
- The inherent complexity of the project (13 %)
- Changing or expanding the scope of the project (8 %)

4.4 6 Variables in Construction Scheduling

A very detailed list of variables which affect construction schedule is given by Nasir, McCabe and Hartono in their tentative to develop a method to assist the determination of the lower and upper activity duration values (Table 4 11)

4.4 6.1 Environmental variables

The main variable that affects construction activities and also one of the major sources of schedule uncertainty is weather Snow, cold temperature, humidity, rainfall wind velocity, and heat are some of the weather-related factors that can lead to reduced human performance in the form of reduced labor productivity or can result even in work stoppage (Moselhi Gong El-Rayes 1997)

4.4 6 2 Geotechnical variables

Another important source of construction schedule uncertainty that are frequently leading to construction delays are the geotechnical variables, legally called differing site conditions. Because differing site conditions can significantly influence both the schedule and the contract cost, thus profitability It is the one of the most frequently occurring owner-contractor dispute in the construction industry

From the legal point of view there are two types of differing site conditions Type I and Type II differing site conditions Type I differing site condition occurs when subsurface or latent physical condition at the project site materially differs from those indicated in the contract. Type II differing site condition occurs when an unknown physical condition at the site of an unusual nature, differs materially from a similar condition ordinarily encountered and generally recognized as inhering in the work scope as defined by the contract documents Unusual conditions are judged or legally tested by the normal or typical condition type for the area.

An example is the case[4] where the contractor was to excavate and install sewer mains[5] During performance, the contractor encountered a Type I differing site condition when it removed almost five times the amount of limerock than that shown in the boring logs (Nash 1995)

In real world in order to avoid disruptions and to alleviate the unnecessary expense of contractor s site borings and investigations, the typical owner normally obtains information during design programming regarding site conditions The contractor then examines the information via bid documents

General federal law about a contractor's right to base its bid on government specifications establishes that where the Government makes positive statements in the specifications or drawings for the guidance of bidders, the contractor has the right to rely on them regardless of contractual provisions requiring the contractor to make investigations

For the particular case of highway projects one of the leading cause of time delays that fall into the geotechnical variables category are the site utilities. The most prominent problems with site utilities are (Thomas, Ellis 2001)

- Utility relocation
- Coordination
- Relationship (communications and cooperation) with utilities companies
- Unforeseen utility conflicts

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[4] Betancourt & Gonzalez, S E., DOTCAB No 2789 95 1 (1995)

[5] Location was U S Coast Guard Air Station Borinquen Aguadilla, Puerto Rico

Table 4-11 Risk variables in construction scheduling

Risk Variables	Definition	States
1 Environmental		
Earthquake	Area history of an earthquake causing damage	Low/high risk
Seasons	Season that may affect the schedule	Spring and Fall/Summer/Winter
Precipitation	History of precipitation	Generally light/heavy
Humidity	Effect of humidity on the progress of work	Low/high
2 Geotechnical		
Archaeological survey done	Was archaeological survey done –historical buildings etc.?	No/yes
Local geotechnical history	Geotechnical history of the area	Favorable/unfavorable
Geotechnical consultant	Experience of consultants in similar area and project scale	Experienced/inexperienced
Unexpected subsurface conditions	Unknown conditions that may result in delay	Low/high risk
3 Labor		
Labor union	The labor to be entirely union or a mix	Open/closed shop
Labor dispute/strike	The risk of labor disputes	Low/high risk
Labor availability	Are all labor abundantly available in the area?	Yes/no
Labor wage scales	Local prevalent wages of skilled and unskilled labor	High/moderate/low
Labor skill level	Competency level of labor	High/moderate/low
Potential for adverse activities	Risk that labor may actively delay progress	Low/high risk
Labor injuries	Risk to injury local activity, and regard to site safety	Low/high risk
Labor productivity	General output of labor	High/moderate/low
4 Owner		
Owner type	Type of owner	Private/public/nonprofit
Owner financial stability	Financial stability of owner with respect to project	Sound/risky
Decision making	Efficiency of decision making by the owner	Efficient/inefficient
Progress payment	Progress payments at time specified in contract	On Time/delayed
5 Design		
Fast track schedule	Is design and construction running concurrently?	Yes/no
Design team	Experience of design group in type and size of project	Experienced/inexperienced
Multifunctional building	A multifunctional building may be more complex	Yes/no
Project definition	The degree to which the project scope is defined	Complete/incomplete
Innovative complex design	Design requiring unique details for various components	Yes/no
Design specifications	Degree of design specification completeness	Complete/incomplete
Design quality	Design quality in terms of design reviews or rework	High/low quality
Design changes	Risk that design changes will affect work progress	Low/high risk

Table 4.11 Risk variables in construction scheduling (continued)

6 Area condition		
Construction area	Site location	Outside/inside metro
Reconstruction project	Significant demolition rehabilitation, in operating facility	No/yes
External site activity	Other site activity outside of construction	Yes/no
Traffic conditions	Traffic may affect movement of people materials to site	Efficient/slow
On-site congestion	Is movement of equip people materials affected?	Open/congested
Traffic permits and approvals	Permits and approvals including traffic diversions	Few/excessive
Intense security	Is intense security required in the area?	Not required/required
Working hour restriction	Are work time restrictions in place	No/yes
7 Political		
Community attitude	Standpoint of the local residents toward the project	Friendly/hostile
Strong dissenting group	Is a strong influential group against the project?	No/yes
Relevant public inquiries	Any current public inquiries related to project?	None/going on
Potential of delay by others	The chance of delay by parties outside the contract	Low/high risk
Project stopped abandoned	Chance of project stopped or abandoned entirely	Low/high risk
8 Contractor		
Contractor prequalified	Will the contractors be prequalified?	Yes/no
Contractor experience	Contractor s experience and ability including staff profiles	High/average/low
New technology	Will new construction methods be used?	Yes/no
Defective work	Risk of defects that necessitate rework	Low/high risk
Rework	The chance of frequent reworks needed	Low/high risk
Short breaks	Risk of many short breaks affecting productivity	Low/high risk
9 Contractor non labor resources		
Vendor bondability	Is vendor bonded to supply items for a specified time?	Yes/no
Critical items import	Are critical equipment or materials being imported?	On time/delayed
Equipment quality	Condition of contractor s equipment	Good/poor
Theft of equipment and tools	Chances of theft of equipment and tools affecting work	Low/high risk
Damage to equipment	Risk of damage to equipment by mishandling, low skill	Low/high risk
Equipment failure	The chance of equipment failure	Low/high risk
Equipment shortage	The chance of nonavailability of equipment	Low/high risk
10 Material		
Reliance on JIT delivery	Level of reliance on just in time material delivery	High/low
Secure material yards	Is material yard secured to avoid sabotage or theft?	Yes/no
Material theft/fire	Chance of sabotage of material by anyone	Low/high risk
Material procurement	Status of fabricated or raw material procurement?	On schedule/delayed
Material shortage	The chance of nonavailability of material Low/high risk	On schedule/delayed

4.4 6.3 Labor variables

Labor changes have a powerful impact on construction productivity and further on the construction schedule Labor productivity has a major effect on construction progress Labor strikes, idle workers and labor injuries are some of the major factors that affect labor productivity and finally project duration. Unskilled labor and poor wage scales not only affect productivity but may also result in labor injuries. Labor unions play an important role in providing skilled labor maintaining better labor wages discussed the effects of labor scarcity and surplus on schedules. Labor disputes are another reason for delay of projects

The reassignment of personnel to available work usually causes a density problem where the work is available The scheduled task has been laid out in a logical manner and it is more than probably that it was already allocated at a reasonable level But in order to achieve percentage completion the contractor is forced to work in a non-optimum situation and which affects productivity considerably

Another typical situation which influences labor productivity relates to the way construction works are scheduled in highway reconstruction projects

In the United States, 85% of SHAs are scheduling night reconstruction (Russel et.al, 2002) in order to take advantage of the significant decrease in traffic volumes during these times which lead to a decrease in delays for highway users The disadvantages of night work related to labor include increased safety hazards due to fatigue and poor visibility conditions

A research done by the University of Calgary in which 22 highly experienced Canadian experts in Alberta construction Industry, with an average of 27 years of construction experience, have been involved, identified 51 factors that affect construction productivity

The first 15 factors and their rank are given in Table 4-12 The factors were classified in three categories human factors management factors and external factors

Table 4-12 Factors affecting construction productivity

#	Category	Rank	Factors
1	Management	37 13	Lack of detailed planning
2	Human	35 30	Worker experience and skills
3	Management	35 25	Inadequate supervision
4	Human	26 15	Worker motivation
5	Management	25 60	Non availability of materials
6	Human	21 75	Worker attitude and morale
7	Human	20 40	Team spirit of the crew
8	Management	19 20	Non availability of information
9	External	18 85	Changes in drawings and specifications
10	Management	18 75	Non availability of tools
11	Management	18 60	Non availability of equipment
12	Management	17 94	Nature of project (size and complexity)
13	External	16 40	Lack of procedures for construction methods
14	External	11 95	Changes in contract
15	External	11 60	Congested work area

4.4 6.4 Owner variables

The owner might influence directly or indirectly the construction schedule Poor communication slow decision making inexperienced management, inadequate supervision financial problems and late payments are some of the owner s variables

In the particular case of transportation construction projects the owner is a state authority States' commitment of funds for individual projects is governed by rules that can compel projects to be deferred for a number of years. Certain matching restrictions can also delay project delivery

4.4.6.5 Design variables

Incomplete drawings, inaccurate design, and incomplete specifications are other sources of risks. Undefined scope and frequent changes in scope affect many projects. Identified work grouping and preplanning are also important factors affecting a project. Fast-track projects have their own set of inherent risks that may affect materials management or design quality.

4.4.6.6 Area condition variables

Construction in a certain area like downtown for example, brings with it many risks. Site congestion, traffic conditions near and around the site, right-of-way permits and approvals, and staging conditions are some of the main uncertainties and risks related to the construction area. Site access restrictions, security issues or other working restrictions can be added to the list of area conditions variables.

Constructing at an operating facility has also substantial risk, because complaint from users of the facility may cause work stoppages or require night shifts to reduce disturbances created by the construction.

The typical characteristic of highway construction from the area condition point of view is the work zones, where lane closure dramatically affects traffic. In a study sponsored by the Federal Highway Administration (FHWA), a survey of 789 work zones was conducted in order to estimate national-level statistics such as the number of miles on the National Highway System (NHS) with work zones during the peak of the summer roadwork season.

The study revealed that 58% of work zones were active or had lane closures primarily during daylight hours, 33% were primarily night work and 9% were active nearly around the clock. The average work zone had lane closures for 11 hours a day and occupied 6.8 miles of roadway for an average of 125 days.

The most frequent reported purposes for work zones were bridge related roadwork (28%) and pavement operations (24%). Pavement operations had a much higher frequency of night activity: two-thirds of all resurfacing/paving activity was conducted as night work.

The correlation between the work zone and the project duration showed that from 71% of the work zones studied the average project duration were 125 days and a median of 65 days (Figure 4-4).

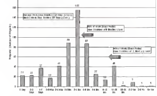

Figure 4-4 Distribution of work zone duration

Day work average duration and night work average duration were quite similar (roughly 9 hours) but that day work had wider variation. The study (Wunderlich, Hardesty 2003) also showed that 33% of work zones had capacity impacts primarily at night, 58% in the daytime hours, and 8% all day or nearly all day (18+ hours). The most frequent hour of work zone capacity impact was 9 AM to 10 AM, when 67% of the work zones were found to be either active or have lane closures, while the least frequent hour was 6 PM to 7 PM when only 19% of work zones were found to have a capacity impact (Figure 4-5).

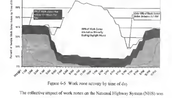

Figure 4-5 Work zone activity by time of day

The collective impact of work zones on the National Highway System (NHS) was estimated at 2 672 lane miles of freeway, or roughly the carrying capacity associated with one direction (three lanes) of a six lane interstate connecting Washington, DC to St. Louis, MO (Wunderlich, Hardesty 2003)

4 3 6 7 Political variables

Political risks can be the result of government instability, changes in requirements of permits or approvals

Many construction projects involve and influence a broad range of governmental agencies and public interest groups with diverse concerns. Some of the projects require review of concepts and plans to assess compliance with statutory limitations. Others require approval of plans and specifications for construction that affects properties or facilities. Interested parties will want to contribute or influence ideas.

Projects that cross jurisdictional boundaries and navigable waterways introduce additional requirements in the number and extent of involvement of both regulatory bodies and affected agencies. The St. Louis Light Rail Project for example, involved the federal government, two states, the City of St. Louis, St. Louis County in Missouri, the City of East St. Louis, Illinois, and a multitude of participating and affected agencies.

A factor that is sometimes overlooked is the interfacing of the contractors with the community and the desirability of community involvement related to the project. A project's schedule can be greatly damaged by poor performance in responding to and coordinating with the community during the construction.

4.4.6.8 Contractor variables

A first contractor related variable is created by the process of selecting the contractor itself. Traditionally selection process is based on the "lowest bid" criterion which offers little information on contractor's capabilities and performance.

Innovative contracting techniques like A+B (Cost + Time), Incentive/Disincentive, and Lane Rental, have been introduced in transportation construction projects in an attempt to reduce uncertainty factors related to this aspect.

The A+B (Cost plus time) contracting technique encourages the contractor to capitalize on a particular construction method or process that would speed construction

In most cases, it is the contractor who can best determine the most reasonable amount of time necessary to complete the project.

In the incentive/disincentive (I/D) contracting technique bonuses and penalties are assessed on a daily basis and can be used to achieve specific milestones within a project or to encourage timely completion of the total contract.

A survey of the U S Departments of Transportation (DOTs) and selected agencies in Canada done by the Transportation Research Board (TRB 2000) showed that 94% of the agencies use incentives/disincentives type of contracting 76% use cost-plus-time (A+B method), and 52% use lane rental as shown in Figure 4-6

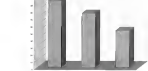

Figure 4-6 DOTs use of contracting methods

In the design/build contracts the bid packages are awarded based on design quality timeliness, management capability, and environmental sensitivity By allowing the contractor to optimize its workforce equipment, and scheduling, the design/build concept offers a degree of flexibility for innovation

From the agencies perspective the potential time savings is a significant benefit. Since design and construction are performed through one procurement, construction can begin before all design details are finalized Additionally since the contractor and designer are the same organization claims are greatly reduced

A second source of variability is the way projects are subcontracted Many subcontractors are selected only when the time for their portion of work is near which does not allow for thorough evaluation of the subcontractor's experience and ability to meet project demands

A third source of uncertainty is the large variety of completely independent participating entities in each project If the general contractor does not have a global and systemic view of the supply chain of projects the individually optimal combination may not result in the best global outcome

Another factor that has the potential to affect the construction schedule is the contractor's decision to deploy novel technology or methods of construction into the project.

4.4.6.9 Contractor resources (non-labor) variables

Equipment availability and quality can cause disruption of work which will definitely affect the construction schedule The originally planned work is organized according to an orderly flow of manpower and equipment using a logical sequence of work activities When this orderly plan is impacted by a change such as late deliveries of equipment, labor productivity is also affected, and the effect propagates over the construction schedule

When a late equipment delivery takes place the contractor is forced to work outside the normal logical flow of activity sequencing in order to meet the end date of the job which in most cases is a fixed one. The rhythm of the project will be affected at its turn which will result in more fragmentation of work activities impeding also the chance to take advantage of the normal learning curve.

4.4.6.10 Material variables

Uncertainties related to material resources represent also an important constraint in scheduling construction projects.

The impact these uncertainties have on the construction schedule is in a way similar to the impact of uncertainties related to equipment. Availability or shortage of construction materials, and late delivery or procurement of materials affect labor productivity and implicit the construction schedule.

Another uncertain factor is the quality of construction materials. The increasing complexity of construction materials due to diverse embedded technology needed for safe and reliable production and products creates particular problems related to their usage. New materials are being developed and utilized for their better material properties or behavior in specific cases and also for their economically affordable production. What is not always known is their total effect for the whole system efficiency and performance in the construction environment.

4.5 Factors Affecting Contract Duration in Transportation Projects

Previous paragraphs revealed a large variability and different approaches and classifications of the uncertainty factors and variables that affect the elements of the construction schedule, particularly project duration.

The present research is concerned mainly with the problem of uncertainty in scheduling repetitive construction projects. Transportation construction projects are one of the most representative repetitive types of construction.

In conformity to the goal of the proposed research factors that affect contract duration of transportation projects were identified and ranked.

4.5.1 Data Collection

The data used in this research endeavor is available at the FDOT Construction Office, and it was provided by the State Construction Office.

The data consisted in spreadsheets of cost-time summary for contracts completed during the fourth quarter of the fiscal year 2001/2002.

There are three levels of detail of contracts' cost and time as provided by FDOT.

The first one is presents summary of time and cost for each district, and also a total for the quarter analyzed. Part of this report is shown in Table 4-13. The table reveals only the fields that contain data related to the duration of the project and the time extensions because it is considered they are of direct relevance for the present research.

Table 4-13 Summary of the fourth quarter (2001/2002)

District	Original Contract Days	Weather Days		Time Extensions		Supplemental Agreement		Present Days	Days Used	Days Used (Less Weather)	% Increase (Less Weather)
		Days Added	% of Original Days	Days Added	% of Original Days	Days Added	% of Original Days				
01	10,850	982	9.05%	715	6.59%	1,127	10.39%	13,674	13,651	12,669	16.76%
02	14,494	1,695	11.77%	1,244	8.64%	1,834	12.73%	19,177	18,673	16,978	17.87%
03	13,069	2,778	21.26%	741	5.67%	786	6.01%	17,379	17,846	15,068	15.30%
04	10,655	615	5.77%	1,057	9.92%	1,308	12.28%	13,635	13,163	12,548	17.77%
05	10,233	1,182	11.55%	447	4.37%	758	7.33%	12,619	12,462	11,280	10.23%
06	7,549	524	6.94%	217	2.87%	111	1.47%	8,401	8,272	7,748	2.64%
07	8,094	636	7.86%	963	11.90%	1,217	15.04%	10,910	11,245	10,609	31.07%
08	5,671	60	1.06%	457	8.06%	1,389	24.49%	7,577	7,411	7,351	29.62%
Totals This Qtr	80,525	8,472	10.52%	5,841	7.25%	8,522	10.58%	103,365	102,723	94,251	17.05%

The table shows the information related to total days (original days, weather days, time extensions days supplemental agreements days present days and days used), as well as the percentages of increase to the original contract duration

It can be noticed that weather days contributed to the increase of the original contract durations by 10 52% while the increase due to time extensions and supplemental agreements reached a percentage of 17 05%

The second report gives statewide information, partially shown in Table 4-14 The report provides the original contract days as well as present contract days, where data on time extensions due to supplemental agreements, work orders, and inclement weather were added

Time extensions are detailed in conformity with the main types of work orders that created the extensions as follows

- Changed conditions work orders
- Plans modifications work orders
- Specifications modifications work orders
- Value engineering work orders
- Partnering work orders
- CEI action/in action work orders
- Minor changes work orders
- Defective materials work orders
- Weather related damage work orders
- Claims work orders
- Utility delays work orders
- Invalid reasons codes work orders

For each type of work order the table's fields present data on time extensions, supplemental agreements days, supplemental agreement amount and premium cost. For space and significance reasons, only the fields containing data related to contract days are presented in Table 4-14

The third report contains the same fields as those presented in the statewide report. The level of detail of this report refers to each contract in work at each district (from district 1 through district 8). Cost and time data are given for a total of 323 contracts. The report also gives information related to the parties involved in the contract, and also the type of contract used.

Table 4-14 Statewide FDOT cost and time report

District	Original Contract Days	Present Contract Days	Days Used	Unused Days	Delinquent Days	Time Extension	SA Days
District 1 Totals	10850	13674	13651	23	268	1714	1118
District 2 Totals	14404	19177	18673	504	152	3367	1650
District 3 Totals	13069	17379	17846	-467	759	3565	745
District 4 Totals	10655	13635	13163	472	0	1672	1388
District 5 Totals	10233	12612	12462	150	348	1771	618
District 6 Totals	7549	8401	8272	129	563	741	111
District 7 Totals	8094	10910	11245	335	587	1599	1217
District 8 Totals	5671	7577	7411	166	2	517	1389
Statewide Totals	80525	103365	102723	642	2679	14946	8138

4.5.2 Data Analysis Methodology

For the purpose of the analysis, the first step was to filter the data including only the duration-related contributing factors. These filtered databases are included in Appendix C and Appendix D. Some descriptive statistics were drawn from the filtered data to have a better idea of the data composition. This analysis is shown in the following figures and table.

Figure 4-7 shows the percentages the weather days, time extensions corresponding to work orders and time extensions corresponding to supplemental agreements contribute to the increase of the original contract duration. It can be noticed that all three categories have comparable effect on the original value of the contract duration.

Figure 4-8 shows the percentage of days increase in contract days due to different types of work orders. It can be noticed that changed conditions work orders have the highest influence (44%) on contract duration, followed closely by plan modifications (23%) and construction engineering and inspection (CEI) with a percent of 23%. All three account for 90% of the time extensions due to work orders.

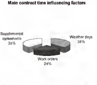

Figure 4-7 Factors that influence contract duration

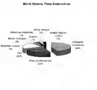

Figure 4-8 Contribution of work orders to contract time extension

Figure 4-9 illustrate the ranking of all elements whose influence on the original contract duration was computed by FDOT The percentages show the contribution each type of uncertain factor had to the increase of the original contract duration

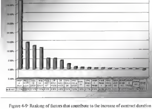

Figure 4-9· Ranking of factors that contribute to the increase of contract duration

From the above rank we can notice that weather days contribute to the increase of original contract duration by 37 10%, followed by plans modification (14 40%) changed conditions work orders (12.70%), changed conditions supplemental agreements (11 00%), plans modification work orders (5 9%) and CEI work orders (5 8%)

The 80/20 rule applies to the factors that affect contract duration as well, because 20% of the factors can be accounted for more than 80% of the days increase of contract duration.

Value engineering is the only factor that has a positive effect on contract duration Per total FDOT contracts, value engineering contributed with a decrease of 133 days

Figure 4-10 depicts the percentage each type of supplemental agreements (SAs) contributes to the increase of contract duration. It can be noticed that supplemental agreements due to plans modifications have the most influence on original contract duration (37%), followed closely by supplemental agreements due to change orders (33%) Significant influences have also the SAs due to CEI (13%) and SAs due to utility delays (8%)

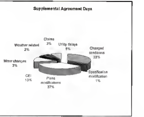

Figure 4-10 Influence of supplemental agreements on contract duration

A final analysis of the elements that influence original contract duration in transportation construction projects is presented in Table 4-15 Data on the type of innovative contracting method used offered the basis for this analysis (Appendix E) The table presents an indirect analysis, as it is difficult to establish a correlation between the type of contract and the increase of project duration

Table 4-15 Influence of innovative contracting methods on contract duration

Innovative contracting method	Total original contract days	Total present contract days	Absolute difference	%	Average percentage
Lump sum	3566	4346	780	22%	22%
Bonus	7291	7716	425	6%	4%
Incentive / Disincentive	6542	7632	1090	17%	17%
A+B Bidding	4295	5018	723	17%	21%
Liquidated Savings	2155	2666	511	27%	29%

4.5.3 Sensitivity Analysis of Uncertain Factors

The descriptive statistics analysis completed in the previous paragraph helped to identify the main factors that influence the original contract duration of transportation construction projects.

In order to continue the process of uncertainty assessment a sensitivity analysis will be performed, because sensitivity analysis offers a good indication concerning the contribution of each factor to the uncertainty of the project duration. The higher the sensitivity of the original contract duration to a factor the higher will be the contribution of that factor to the uncertainty of the project duration, and schedule respectively.

A nominal range sensitivity analysis (NRSA) will be performed by holding all factors except one at their nominal values while varying the remaining factor from its low-end (MIN) to high-end (MAX) range estimate.

A final statistic computed as part of the nominal range sensitivity analysis is the normalized nominal range sensitivity calculated by dividing the nominal range sensitivity for parameter i by the sum of nominal range sensitivities for all parameters.

The normalized nominal range sensitivity provides an estimate of the relative sensitivity of relative net influence of each parameter uncertainty The normalized nominal range sensitivity falls between 0 and 1

Parameters with higher normalized nominal range sensitivities create greater uncertainty about relative duration increase than parameters with lower normalized nominal range sensitivities Because they are relative values normalized nominal range sensitivities are only comparable across parameters

The analysis will be performed for 281 projects (from the total of 323 transportation construction projects) that presented variations of the original contract duration (Table 4 16)

For a more detailed investigation of the influences of various uncertain parameters, three more sensitivity analysis will be performed, by dividing the projects in respect to their original contract duration as follows

- Short projects: projects with a original contract duration between 1 month and 3 months (Table 4-17)
- Medium projects projects with a original contract duration between 3 months and 1 year (Table 4-18)
- Long projects: projects with a original contract duration higher than 1 year (Table 4-19)

The normalized nominal range sensitivity for the 281 transportation construction projects shows that the greatest contributor to uncertainty are the plan modifications (SA) uncertainty (23.18%) followed by CEI (SA) uncertainty (12 45%) and changed conditions (SA) uncertainty (11 32%) Weather days uncertainty ranks fourth with a normalized nominal range sensitivity of 7 14%

Table 4-16 NRSA for total transportation construction projects

Parameter	Low end Nominal Range Estimate	High-end Nominal Range Estimate	Nominal Range Sensitivity	Normalized Nominal Range Sensitivity
Weather Days	0	253	253	7.14%
Changed Conditions (WO)	0	189	189	5.34%
Changed Conditions (SA)	-4	397	401	11.32%
Plans Modifications (WO)	0	250	250	7.06%
Plans Modifications (SA)	-193	628	821	23.18%
Specifications (WO)	0	0	0	0.00%
Specifications (SA)	0	45	45	1.27%
Value Engineering (WO)	0	0	0	0.00%
Value Engineering (SA)	30	80	110	3.11%
Partnering (WO)	0	0	0	0.00%
Partnering (SA)	0	0	0	0.00%
CEI (WO)	-44	164	208	5.87%
CEI (SA)	-60	381	441	12.45%
Minor Changes (WO)	0	28	28	0.79%
Minor Changes (SA)	0	81	81	2.29%
Defective Materials (WO)	0	38	38	1.07%
Defective Materials (SA)	0	0	0	0.00%
Weather Related (WO)	0	9	9	0.25%
Weather Related (SA)	0	40	40	1.13%
Claims (WO)	0	39	39	1.10%
Claims (SA)	0	234	234	6.61%
Utility Delays (WO)	0	72	72	2.03%
Utility Delays (SA)	0	222	222	6.27%
Invalid Reason WO	0	58	58	1.64%
Invalid reason SA	0	3	3	0.08%

Table 4-17 NRSA for short term projects

Rank	Parameter	Low and Nominal Range Estimate	High-end Nominal Range Estimate	Nominal Range Sensitivity	Normalized Nominal Range Sensitivity
3	Weather Days	0	74	74	12.50%
4	Changed Conditions (WO)	0	65	65	10.98%
6	Changed Conditions (SA)	0	34	34	5.74%
1	Plans Modifications (WO)	0	177	177	29.90%
2	Plans Modifications (SA)	0	79	79	13.74%
3	CEI (WO)	0	74	74	12.50%
7	CEI (SA)	0	21	21	3.55%
11	Weather Related (SA)	0	3	3	0.51%
5	Claims (SA)	0	39	39	6.59%
9	Utility Delays (WO)	0	3	3	0.51%
10	Utility Delays (SA)	0	0	0	0.00%
8	Invalid Reason (WO)	0	20	20	3.38%
0	Invalid reason (SA)	0	3	3	0.51%

The normalized nominal range sensitivity for short term projects presented in Table 5-17 shows that once again the plan modifications (SA) uncertainty (29.90%) has the highest contribution to the increase of original contract duration. Plans modification (SA) ranks the second (13.74%), while CEI (SA) uncertainty and weather days uncertainty rank both the third (12.50%). The next highest contributions to the changes in contract duration have the changed conditions (WO) uncertainties (10.98%).

Claims work orders uncertainties have a significant influence on original contract duration at their turn but because the data does not specify the nature of this claims they will ignored in the process of uncertainty assessment.

Table 4-18 NRSA for medium term projects

Rank	Parameter	Low-end Nominal Range Estimate	High-end Nominal Range Estimate	Nominal Range Sensitivity	Normalized Nominal Range Sensitivity
4	Weather Days	0	235	235	11.71%
7	Changed Conditions (WO)	0	163	163	8.12%
1	Changed Conditions (SA)	-4	397	401	19.98%
3	Plans Modifications (WO)	0	250	250	12.46%
5	Plans Modifications (SA)	0	170	170	8.47%
9	Specifications (SA)	0	45	45	2.24%
8	Value Engineering (SA)	2	80	82	4.09%
6	CEI (WO)	3	164	167	8.32%
2	CEI (SA)	10	252	262	13.05%
12	Minor Changes (WO)	0	28	28	1.40%
10	Minor Changes (SA)	0	40	40	1.99%
11	Defective Materials (SA)	0	38	38	1.89%

For medium term projects the changed conditions (SA) uncertainties rank first (19.98%) CEI (SA) uncertainty second (13.05%), plans modifications (WO) uncertainties third (12.46%), weather days uncertainty fourth (11.71%) and plans modifications (SA) fifth (8.47%), followed closely by CEI (WO) uncertainties (8.32%) and changed conditions (WO) uncertainties (8.12%).

After analyzing the long term projects and the factors that affect their original contract duration the conclusion is that plans modification (SA) uncertainties have the most influence on contract duration (23.03%) followed by CEI (SA) uncertainties (14.13%), changed conditions (SA) uncertainties (12.36%), and weather days uncertainties (9.28%)

Table 4-19 NRSA for long term projects

Rank	Parameter	Low end Nominal Range Estimate	High-end Nominal Range Estimate	Nominal Range Sensitivity	Normalized Nominal Range Sensitivity
4	Weather Days	0	253	253	9 28%
7	Changed Conditions (WO)	0	189	189	6.93%
3	Changed Conditions (SA)	0	337	337	12 38%
11	Plans Modifications (WO)	0	60	60	2.20%
1	Plans Modifications (SA)	0	828	328	23 03%
8	CEI (WO)	0	121	121	4.49%
2	CEI (SA)	0	381	381	14 13%
14	Minor Changes (WO)	0	14	14	0.52%
9	Minor Changes (SA)	0	81	81	3%
15	Weather Related (WO)	0	5	5	0 19%
13	Weather Related (SA)	0	40	40	1.48%
5	Claims (SA)	0	234	234	8 68%
10	Utility Delays (WO)	0	72	72	2.67%
6	Utility Delays (SA)	0	222	222	8.23%
12	Invalid Reason WO	0	58	58	2 15%
16	Invalid reason SA	0	2	2	0 07%

4 6 Summary and Conclusions

Making a reliable estimation of project duration is one of the major problems in construction project scheduling. This reliability is dependent upon the accuracy of estimating the effect of various time influencing factors in the construction project environment

Schedulers usually make use of their own intuition and experience in order to consider the effect of the time factors on the schedule but the most common approach is to treat data as if it were precisely known However the information that the scheduler has about the system's parameters is in most cases vague and imprecise resulting in a schedule that will perform poorly in real world instances

From the theories and methods used to assess uncertainties in the scheduling process, the fuzzy set theory was proved to be the most proper tool to be used when dealing with vagueness and ambiguity of scheduling parameters

An analysis of time data from 323 transportation construction contracts helped to identify which are the main factors that affect the original contract time After eliminating the projects that were not affected by any factors 281 projects were studied.

A positive aspect of this analysis is the fact that the factors analyzed come from databases that already exist and from documents provided by FDOT By using the same terminology and data gathered by FDOT the assessment of uncertainty in scheduling repetitive construction processes will offer a valuable tool easily recognizable by practitioners

Another plus is the fact that by using and interpreting the existing databases, the research will be tailored according to the present system of data collection used by transportation agencies

A matrix synthesizing the ranking results from the sensitivity analyses performed is provided in Table 4-20 From the table we can notice that the uncertain factors rank differently according to the duration of the project

The assessment of uncertainty to repetitive construction projects will be continued by using the same subdivision of projects according to their original contracting duration short term project, medium term project, and long term projects

Table 4-20 Synthesis of uncertain parameters

Parameter	Rank / Type of projects (No.)		
	Short term projects (58)	Medium term projects (156)	Long term projects (67)
Weather Days	**3**	**4**	**4**
	12.50%	11.71%	9.28%
Changed Conditions (WO)	**4**	**7**	**7**
	10.98%	8.12%	6.93%
Changed Conditions (SA)	**6**	**1**	**3**
	5.74%	19.98%	12.36%
Plans Modifications (WO)	**1**	**3**	**11**
	29.90%	12.46%	2.20%
Plans Modifications (SA)	**2**	**5**	**1**
	13.74%	8.47%	23.63%
Value Engineering (SA)	0	**8**	0
		4.09%	
CEI (WO)	**3**	**6**	**8**
	12.50%	8.32%	4.49%
CEI (SA)	**7**	**2**	**2**
	3.55%	13.05%	14.13%
Minor Changes (SA)	0	**10**	**9**
		1.99%	3%
Claims (SA)	**5**	0	**5**
	6.59%		8.66%
Utility Delays (WO)	**9**	0	**10**
	0.51%		2.67%
Utility Delays (SA)	0	**0**	**6**
			8.23%

CHAPTER 5
UNCERTAINTY ASSESSMENT USING FUZZY SETS

5.1 Basics of Fuzzy Set Theory

The fuzzy systems are dynamic, parallel processing systems that estimate input output functions. They estimate a function without any mathematical model and learn from experience with sample data.

As shown in the previous chapter, fuzzy set theory was developed specifically to deal with uncertainties that are not statistical in nature. The main idea of the fuzzy set theory is quite intuitive and natural. Instead of determining the exact boundary as in an ordinary set, a fuzzy set allows no sharply defined boundaries because of the generalization of a characteristic function to a membership function.

In a paper published in 1965 by Lotfi Zadeh, entitled "Fuzzy Sets" (Zadeh, 1965) the multivalence principle was applied to set theory with Zadeh introducing the term "fuzzy" for multivalence sets. The objects in these sets have a different degree of belonging to this set. The "degree of belonging to" is called the membership of an object.

Fuzzy sets are a generalization of discrete set theory and are characterized by three concepts (Burrough, 1993)

- generality – single concept
- ambiguity – single concept embraces more than one sub-concept
- vagueness – precise boundaries are not defined

Conventional or crisp[1] sets allow only a true-false membership function, with elements either belonging to a set or not.

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[1] The term "crisp" means not fuzzy

Fuzzy sets however admit the possibility that a value has partial membership of a class Thus, boundaries are not exactly defined The general notation of fuzzy sets is (Burrough, 1993, Klir Wierman 1998)

$$A(x)=\lfloor X,\mu_{A(x)}\rfloor \tag{5 1}$$

Where $A(x)$ = fuzzy set

X = number x

$\mu_{A(x)}$ = degree of membership of x in A

Usually the degree of membership is a number in the range 0 to 1 with 1 representing full membership and 0 representing non membership. The degree of membership does not depend on a probability but on an admitted possibility (Klir, Wierman, 1998) Thus fuzzy sets can be used in capturing representing and working with linguistic notions or objects that have unclear boundaries.

A fuzzy set initiated by Zadeh is defined as follows

> Let X denote a universal set Then a fuzzy subset A of X is defined by its membership function $f_A\ X\rightarrow[0\,1]$ which assigns to each element $x\in X$, a real number $\mu_{A(x)}$ in the interval $[0,1]$ where the value of $f_A(x)$ at x represents the grade of membership of x in A Thus, the nearer the value of $f_A(x)$, is unity the higher the grade of membership of x in A

A fuzzy subset A can be characterized as a set of ordered pairs of element x and grade $f_A(x)$ and is often written as $A=\{(x\ f_A(x))\mid x\in X\}$

When the membership function $f_A(x)$ contains only the two points 0 and 1, then $f_A(x)$ is identical to the characteristic $c_A{:}X\longrightarrow\{0,1\}$ and hence, A is no longer a fuzzy subset, but an ordinary set A

An ordinary set A is expressed as $A = \{x \in X / c_A(x) = 1\}$ through its characteristic function

$$c_A(x) = \begin{Bmatrix} 1 & x \in A \\ 0 & x \notin A \end{Bmatrix} \tag{5-2}$$

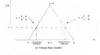
The degrees of belief are either directly obtained through verbal statements such as *high*, *very low* and so on, or they are inferred from the vague evidence expressed linguistically in a similar way. In such situations, it is difficult to avoid arbitrariness in the assignment of a precise number, or even an interval, to each hypothesis.

Among the various types of fuzzy sets, those defined on the set R of real numbers are of special significance. Membership functions of these sets, which have the form $A: R \to [0,1]$, evidently have a quantitative meaning.

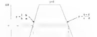
Under certain conditions these functions can be look upon as fuzzy numbers of fuzzy intervals. To view them in this way, they should capture intuitive conceptions of approximate numbers or intervals, such as numbers that are close to a given real number or numbers that are around a given interval of real numbers. Such concepts play a key role in many applications, including fuzzy control, decision-making, approximate reasoning, optimization and statistics with imprecise probabilities.

The fuzzy numbers will be almost always triangular (shaped) or trapezoidal (shaped) fuzzy numbers as shown in Figure 5-1 (Leu, Chen, Yang, 2001). Triangle and trapezoidal fuzzy numbers are commonly used to represent activity durations.

Fuzzy logic is a superset of conventional (Boolean) logic that has been extended to handle the concept of partial truth. Truth values range between *completely true* and *completely false*.



(a) Triangle fuzzy number



(b) Trapezoidal fuzzy number

Figure 5-17 Triangle and trapezoidal fuzzy numbers

Zadeh states that the process of fuzzification should be regarded as a methodology to generalize any specific theory from a crisp (discrete) to a continuous (fuzzy) form

5.2 Linguistic Variables

5.2.1 Introduction to the Concept of Linguistic Variables

The concept of linguistic variables lies at the core of Fuzzy Set Theory, since the basics of Fuzzy Set Theory is the manipulation of linguistic expressions instead of numbers (Balor Price, 2003)

The linguistic variables are purely words, and their value is the value of the words describing the variable. The concept of linguistic variables provides a means to characterize too complex or too ill defined phenomena.

Uncertainty factors can be characterized using linguistic variables such as, *weather conditions*, *site conditions*, or *design quality*. These linguistic variables may assume different values such as *very high*, *high*, *moderate*, *low* and *very low*, which are fuzzy sets (membership functions) and represent the perception of the decision-maker on the magnitude of any risk factor. In conclusion a linguistic variable is a fuzzy variable.

5.2.1 Examples of using linguistic variables

The following example will reveal the way fuzzy sets can be used in determining the relationship between people and *tallness*. In this case the set S (the universe of discourse) is the set of people.

Let's define a fuzzy subset *tall*, which will answer the question "to what degree is person *x* tall?" "Tall" in this example is as a linguistic variable, which represents our cognitive category of "tallness". To each person in the universe of discourse, we have to assign a degree of membership in the fuzzy subset *tall*. The easiest way to do this is with a membership function based on the person's height (Table 5-1).

$$\text{TALL}(x) = \left\{ \begin{array}{ll} 0 & \text{if heith}(x) < 5\text{ft} \\ (\text{heith}\,(x) - 5\text{ft})/2\text{ft} & \text{if } 5\text{ft} \le \text{heith}\,(x) \le 7\text{ ft} \\ 1 & \text{if heith}(x) > 7\text{ft} \end{array} \right\} \qquad (5.3)$$

Based on equation 5-3 the fuzzy value for "tallness" can easily be represented in a graphical way in Figure 5-2.

Table 5-1: Degree of membership

Person	**Height**	**Degree of Tallness**
Billy	3' 2"	0.00 (I think)
Yoke	5' 5"	0.21
Drew	5' 9"	0.38
Erik	5' 10"	0.42
Mark	6' 1"	0.54
Kareem	7' 2"	1.00 (depends on who you ask)

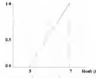


Figure 5-2 Graphical representation of fuzzy value for "tallness"

Expressions like "*A is X*" can be interpreted as degrees of truth, e.g., *Drew is tall*–0.38. Membership functions used in most applications almost never have as simple a shape as the one shown in figure 5-2. At minimum, they tend to be triangles pointing up, and they can be much more complex than that. Also, the discussion characterizes membership functions as if they always are based on a single criterion, but this isn't always the case, although it is quite common. One could, for example, want to have the membership function for *tall* depend on both a person's height and their age (he is tall for his age). This is perfectly legitimate, and occasionally used in practice.

Membership functions of primary terms are subjective and context-dependent. There is no general method to determine membership functions. Whether a particular shape is suitable can be determined only in the application context. The specification of a membership function is a matter of definition. The task of fuzzy logic is to provide rules to compute the meaning of composite terms, once the meaning of the primary terms is specified in a given context.

In Figure 5-3 several different types of profiles that can be used in order to shape the membership function (MF) are presented In certain cases the meaning semantics captured by fuzzy sets is not sensitive to variations in the shape and simple functions are convenient It is also possible to have even more criteria, or to have the membership function depend on elements from two completely different universes of discourse

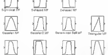


Figure 5-3 Types of membership functions

The next step after showing how fuzzy logic can be used to interpret a statement like *X is LOW* is to try to decode a more complex statement like *X is LOW and Y is HIGH*

The standard definitions in fuzzy logic are

Truth (not x) = 1 0 - Truth (x)

Truth (x and y) = MIN (Truth(x), Truth(y))

Truth (x or y) = MAX (Truth(x), Truth(y))

Some researchers in fuzzy logic have explored the use of other interpretations of the *AND* and the *OR* operations but the definition for the *NOT* operation seems to be safe

It can be observed that when we plug just the values zero and one into these definitions, the result will be the same truth tables that one would expect from conventional Boolean logic. This is known as the Extension Principle, which states that the classical results of Boolean logic are recovered from fuzzy logic operations when all fuzzy membership grades are restricted to the traditional set {0, 1}.

The Extension Principle effectively establishes fuzzy subsets and logic as a true generalization of classical set theory and logic. In fact, by this reasoning all crisp (traditional) subsets are fuzzy subsets of this very special type; and there is no conflict between fuzzy and crisp methods.

Some examples assume the same definition of *TALL* as above, and in addition, assume that we have a fuzzy subset *OLD* defined by the membership function

$$OLD(x) = \left\{ \begin{array}{ll} 0 & \text{if } age(x) < 18\text{years} \\ age(x) - 18 \text{ years} & \text{if } 18 \text{ years} \le age(x) \le 75\text{years} \\ 1 & \text{if } age\,(x) > 75 \text{ years} \end{array} \right\} \quad (5\text{-}4)$$

And for compactness, let

a = X is *TALL* and X is *OLD*

b = X is *TALL* or X is *OLD*

c = not (X is *TALL*)

Then we can compute the following values as shown in Table 5-2.

Table 5-2 Logic operators of *TALL/OLD*

Height	Age	X is TALL	X is OLD	a	b	c
3' 2"	75	0.00	1.00	0.00	1.00	1.00
5' 5"	30	0.21	0.29	0.21	0.29	0.79
5' 9"	27	0.38	0.21	0.21	0.38	0.62
5' 10"	32	0.42	0.33	0.33	0.42	0.58
6' 1"	31	0.54	0.31	0.31	0.54	0.46
7' 2"	45	1.00	0.64	0.64	1.00	0.00
3' 4"	4	0.00	0.00	0.00	0.00	1.00

5.2.2. Hedges

Hedges are a common set of operations on linguistic variables. A hedge is a qualifier on a linguistic variable. It modifies its shape or membership function, to reflect a variation on its semantics. Just as in the English language, hedges are qualifiers for linguistic variables which are not only adjectives, but also verbs, adverbs and certain complete statements. The following are examples of hedges used on different types of variables:

- *very, quite, extremely* - general modifiers
- *quite* true, *mostly* true - truth value modifiers
- *likely, not very* likely - probability modifiers
- *most, several, few* - quantity modifiers
- *almost* impossible, *quite* possible - possibilistic modifiers

Figure 5-4 provides a very useful visualization of the effect of the *very, somewhat and indeed* hedges on membership functions. It can be easily observed that the *medium* and *long* sets which suggest that in this region the variable can have multiple memberships, overcoming the problems of binary logic seen earlier.

Hedges provide a natural, and mathematically simple, way of qualifying fuzzy variables. As a result, the expressive power of a fuzzy representation can be increased at little cost.

5.2.3 Probabilities Assessed to Linguistic Variables

In most fuzzy set based systems parameter identification corresponds to identifying the location of the fuzzy sets that linguistically partition the variable universes.

Quantifying linguistic variables, by attaching numerical probabilities to the variables is a difficult systemic process

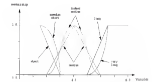


Figure 5-4 Effects of hedges on membership function

The input to the system involves elicitation of expert opinion on conditional probabilities for each variable. Expressing all probabilities numerically is not an easy process because experts might either feel not familiar enough with the concept of probability or because they might find it difficult to attach a number to their beliefs (Renooij, Witteman 1999).

The output is the explanation of the results of computations and it should be easily understandable for the users. Using numbers for explanation of the results may not necessarily be the best option and verbal probability expressions can offer a good alternative as many people communicate probabilities more frequently in words rather than in numbers (Renooij, Witteman, 1999).

Because it is not obvious which verbal probability expressions are more recommended to be used many investigations were done in order to find a set of verbal probability expressions whose meaning is agreed upon and which together cover the whole range from zero to a hundred percent probability.

Renooij and Witteman show a possible combination of probability expressions scale with a probability numerical scale (Figure 5-5)

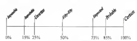


Figure 5 5 Scale of verbal and numerical probabilities
Source Renooij Witteman 1999, pp 191

In the scale proposed by Renooij and Witteman, the boundaries are of course impossible (0%) and certain (100%) The intermediate probability expressions are improbable (15%), uncertain (25%), expected (75%) and probable (85%)

5.3 Operations of Fuzzy Sets

The four fundamental operations with fuzzy sets are complement containment, intersection and union operations

5.3.1 Complement

A complement $\overline{A}$ of a given fuzzy set $A=(0/0,0.75/1,0.25/2,1.0/3)$, is defined as: $\mu_{\overline{A}}(x)=1-\mu_A(x)$ and will be $\overline{A}=(1/0,0.25/1,0.75/2,0/3)$

5.3.2 Containment

A set can be completely contained in a larger set as its subset. Crisp subsets have memberships of 1 since their supersets are existing members of the specified concept. The memberships of a fuzzy subset can have lower membership values than their supersets. That is, an item can belong less to a subset than it does to its parent superset

For example, if $X \in Y$, and $Y=(0/0,0.25/1,0.75/2,0/3)$, then $X=(0/0,0.15/1,0.45/2,0/3)$ is a possibility

5.3.3 Intersection

The classical definition of the intersection of two sets is that which satisfies the conjunction of both the concepts represented by the two sets

Because under fuzzy set theory an item may belong to both sets with differing memberships without having to be in the intersection, in the fuzzy set theory the intersection is therefore defined such that the memberships are the lower or the minimum of the two sets

For example, the intersection of two fuzzy sets long and short defined as follows $long = \{0/0, 0.25/1, 0.75/2, 1.0/3\}$ and $short = \{1.0/0, 0.75/1, 0.25/2, 0/3\}$ is

$$\mu_{long \cap short}(x) = \min\left[\mu_{long}(x), \mu_{short}(x)\right]$$

or

$$\mu_{long}(x) \cap \mu_{short}(x) = \{0/0, 0.25/1, 0.25/2, 0/3\}$$

5.3.4 Union

Following similar arguments to the intersection the union of two sets has memberships which are the larger or the maximum of the two sets Using the same numerical example of the two fuzzy sets *long* and *short* provided above, the union will be $\mu_{long \cup short}(x) = \max\left[\mu_{long}(x), \mu_{short}(x)\right] = \{1.0/0, 0.75/, 0.75/2, 1.0/3\}$

5.3.5 Algebraic Symmetries

The fuzzy set operations obey the same algebraic symmetries as crisp sets (commutativity, associativity, and distributivity) and also fundamental identities (Table 5-3) as follows

- idempotency,
- identity
- involution,

- transitivity
- de Morgan's laws

Table 5.3 Algebraic symmetries of fuzzy sets

COMMUTATIVITY	$A \cup B = B \cup A$ $A \cap B = B \cap A$
ASSOCIATIVITY	$A \cup (B \cup C) = (A \cup B) \cup C$ $A \cap (B \cap C) = (A \cap B) \cap C$
DISTRIBUTIVITY	$A \cup (B \cap C) = (A \cup B) \cap (A \cup C)$ $A \cap (B \cup C) = (A \cap B) \cup (A \cap C)$
IDEMPOTENCY	$A \cup A = A$ $A \cap A = A$
IDENTITY	$A \cup \emptyset = A, A \cap X = X$ $A \cap \emptyset = \emptyset, A \cap X = X$
INVOLUTION	$\overline{(\overline{A})} = A$
TRANSITIVITY	$if (A \subset B) \cap (B \subset C) then A \subset C$
MORGAN'S LAWS	$\overline{(A \cap B)} = \overline{A} \cup \overline{B}$ $\overline{(A \cup B)} = \overline{A} \cap \overline{B}$

5.3.6 Fuzzy Rule Evaluation

Fuzzy rules appear no different to standard rules. They take the familiar form "IF *x* is *A* THEN *y* is B", where *x* and *y* are linguistic variables, and where *A* and *B* are linguistic values.

Under classical logic, the THEN implication is the true value of the IF condition, known as the antecedent. For fuzzy rules, the implication is set to be true to the same degree as the antecedent. Consider the two linguistic variables *length* and *width*, and the rule "IF *length* is *A*, THEN *width* is B". If *A* is instantiated to a value then *B* is assigned to the value such that the membership of B is the same as that for A each to their respective fuzzy sets This process is known as monotonic selection

Antecedents with more than one statement are not a problem as the earlier rules for fuzzy union (disjunction, OR) and intersection (conjunction AND) are applied Similarly for consequents with multiple parts, the resultant antecedent membership is applied to all parts of the consequent

5 4 Fuzzy Inference

Having laid the theoretical foundations of fuzzy set theory, we can proceed to fuzzy inference (Figure 5-6) The following details the whole process of the fuzzification of input variables, fuzzy rule evaluation, combination of the rule consequents and the final defuzzification as performed by using the fuzzy toolbox in MATLAB

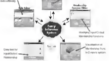


Figure 5 6 The fuzzy inference system

5 4 1 Fuzzification

Real-world crisp data, such as the statistics over a digital image must be fuzzified before it can be subject to fuzzy rules Fuzzification is the process of determining the degree of membership the data has to all appropriate fuzzy sets The essence of this step is therefore in the determination of the form of the fuzzy sets. This can be derived from emperical results or from expert domain knowledge

5.4.2 Rule Evaluation

In some applications, it is desirable to use the operations of union and intersection from probability theory

$$\mu_{A\cup B}(x)=\mu_A(x)+\mu_B(x)-\mu_A(x)\mu_B(x) \quad and \quad \mu_{A\cap B}(x)=\mu_A(x)\mu_B(x)$$

The application of the antecedent evaluation to the consequents is commonly achieved either by **clipping** or **scaling** the consequent membership functions.

Clipping simply places an upper threshold on the consequent membership functions at the level of the antecedent evaluation. Some information about the consequent fuzzy sets is lost during this clipping, but it is used for its computational simplicity. Scaling adjusts the consequent membership functions by multiplying them by the antecedent evaluation result. Although it is used less often, scaling does preserve the forms of the consequent membership functions.

In order to obtain the final fuzzy set rule implications can be combined by summation of the membership functions of the clipped or scaled consequents.

5.4.3 Defuzzification

Real-world problems do require crisp results and so the final fuzzy set is defuzzified. From the large variety of differing definitions for defuzzification, the centre of mass (also named centroid or center of gravity) seems to be the most intuitive and common. The centre of mass of the final fuzzy set is $x=\dfrac{\int\mu_A(x)x\,dx}{\int\mu_A(x)dx}$ evaluated over the universe of discourse for the fuzzy set.

The computation of the center of mass can be simplified by using sums instead of integrals The steps to be taken in a defuzzification procedure are shown in Figure 5 7

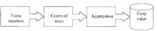


Figure 5 7 Defuzzification steps

5 4 4 Mamdani and Sugeno Inference

The most commonly used fuzzy inference method is the Max-Min inference method or Mamdani inference method which was actually described above

A computationally cheaper alternative to the Mamdani inference is the Sugeno inference. Sugeno replaces the membership degree resulting from the antecedents with a singleton, a Kronecker delta membership function with a value of zero everywhere except at one chosen point where its value is 1 The aggregation therefore leads to a sum of scaled singletons This leaves the defuzzification as a very simple weighted average

The Mamdani inference is more intuitive and well-suited to human input The Sugeno inference is computationally more efficient and well suited to optimization and adaptive techniques and to mathematical analysis. It has also guaranteed continuity of the output space

The methods are very similar as the fuzzification of the inputs and the application of the fuzzy operator are similar However, in Sugeno inference the output membership functions may only be constant or linear

5.5 Fuzzy Scheduling

5.5 1 Fuzzy CPM

In order to present a fuzzy approach to CPM a typical project network characterized by a unique start activity and a unique finish activity is used Activities duration are described by using fuzzy sets as *about 2 about 5 about 8*

The project activities will form the set A , where $i = 1$ through n The activity times are fuzzy numbers t where $i = 1$ through n which have the membership function $\mu_{(\,)}$

The approach in scheduling with fuzzy CPM is as follows (Liberatore, 2002)

- Identify all possible combinations for activity times that lead to a specific critical length
- Consider only those activity times that have positive belief values from the associated membership functions
- Determine the belief associated with each combination of activity times leading to the critical path as the minimum of the beliefs of all the individual activity times in that combination
- Determine the belief of the critical path length as the maximum of the belief values over all combinations
- Repeat the process for all possible critical paths

Figure 5-8 visualizes the membership functions obtained for all the possible critical paths identified in the given example Interpretation of the results can be made as follows

> The duration of the project can be 16 time units with a definite minimum of 14 time units and a definite maximum of 19 time units
>
> Or
>
> We strongly believe that the duration of the project will be 16 time units We also believe that the minimum duration of the project might be 14 time units while the maximum duration can reach 19 time units

Table 5-4 contains the computational iterations taken in scheduling with fuzzy CPM while in

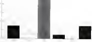


Figure 5-8 Membership function for critical path

An analysis of the previous computational steps in the fuzzy CPM approach brings more clarification to the existing difference between the fuzzy approach and the probabilistic approach in scheduling under uncertainty

While the above presented fuzzy CPM computation used the MIN-MAX approach in establishing activity times, in a probability analysis of a project network, it is well known (Liberatore 2002) that in order to obtain the probability associated with each combination of activity times leading to a specific value for the critical path the methodology consists in multiplying the probabilities of all individual activity times in the combination The probability of a specific critical path length will be the sum of the probabilities over all combinations yielding that length

When activity durations are deterministic after performing the forward and the backward passes of CPM calculation the critical path can be identified based on the zero slack definition However the fuzzy subtraction methods have their drawbacks so the calculations by the backward pass may give meaningless estimates

Table 5-4 Fuzzy critical path example

Activities							Paths			
A	B	C	D	E	F	G	P_1	P_2	P_3	Belief
3	1	4	1	5	1	2	14	8	11	0.1
3	1	4	1	5	2	2	14	9	12	0.1
3	1	4	1	5	4	2	14	11	14*	0.1
3	1	4	1	7	1	2	16*	8	11	0.1
3	1	4	1	7	2	2	16	9	12	0.1
3	1	4	1	7	4	2	16*	11	14	0.1
3	1	4	1	10	1	2	19*	8	11	0.1
3	1	4	1	10	2	2	19*	9	12	0.1
3	1	4	1	10	4	2	19*	11	14	0.1
3	1	4	3	5	1	2	14*	10	13	0.3
3	1	4	3	5	2	2	14*	11	14*	0.3
3	1	4	3	5	4	2	14	13	16*	0.3
3	1	4	3	7	1	2	16	10	13	0.3
3	1	4	3	7	2	2	16*	11	14	0.3
3	1	4	3	7	4	2	16	13	16*	0.3
3	1	4	3	10	1	2	19*	10	13	0.3
3	1	4	3	10	2	2	19	11	14	0.3
3	1	4	3	10	4	2	19	13	16	0.3
3	1	4	4	5	1	2	14	11	14*	0.1
3	1	4	4	5	2	2	14	12	15*	0.1
3	1	4	4	5	4	2	14	14	17	0.1
3	1	4	4	7	1	2	16*	11	14	0.1
3	1	4	4	7	2	2	16*	12	15	0.1
3	1	4	4	7	4	2	16	14	17	0.1
3	1	4	4	10	1	2	19*	11	14	0.1
3	1	4	4	10	2	2	19*	12	15	0.1
3	1	4	4	10	4	2	19*	14	17	0.1
3	2	4	1	5	1	2	14*	9	11	0.1
3	2	4	1	5	2	2	14*	10	12	0.1
3	2	4	1	5	4	2	14*	12	14	0.1
3	2	4	1	7	1	2	16*	9	11	0.1
3	2	4	1	7	2	2	16*	10	12	0.1
3	2	4	1	7	4	2	16*	12	14	0.1
3	2	4	1	10	1	2	19*	9	11	0.1
3	2	4	1	10	2	2	19	10	12	0.1
3	2	4	1	10	4	2	19*	12	14	0.1
3	2	4	3	5	1	2	14*	11	13	0.3
3	2	4	3	5	2	2	14*	12	14*	0.3
3	2	4	3	5	4	2	14	14	16*	0.3
3	2	4	3	7	1	2	16*	11	13	0.5
3	2	4	3	7	2	2	16*	12	14	1.0
3	2	4	3	7	4	2	16*	14	16	0.4
3	2	4	3	10	1	2	19*	11	13	0.3
3	2	4	3	10	2	2	19	12	14	0.3
3	2	4	3	10	4	2	19	14	16	0.3
3	2	4	4	5	1	2	14	12	14	0.1
3	2	4	4	5	2	2	14	13	15*	0.1
3	2	4	4	5	4	2	14	15	17	0.1
3	2	4	4	7	1	2	16	12	14	0.1
3	2	4	4	7	2	2	16*	13	15	0.1
3	2	4	4	7	4	2	16	15	17	0.1
3	2	4	4	10	1	2	19*	12	14	0.1
3	2	4	4	10	2	2	19*	13	15	0.1
3	2	4	4	10	4	2	19*	15	17	0.1
3	3	4	1	5	1	2	14*	10	11	0.1
3	3	4	1	5	2	2	14*	11	12	0.1
3	3	4	1	5	4	2	14*	13	14	0.1
3	3	4	1	7	1	2	16*	10	11	0.1
3	3	4	1	7	2	2	16*	11	12	0.1
3	3	4	1	7	4	2	16*	13	14	0.1
3	3	4	1	10	1	2	19*	10	11	0.1
3	3	4	1	10	2	2	19*	11	12	0.1
3	3	4	1	10	4	2	19*	13	14	0.1
3	3	4	3	5	1	2	14*	12	13	0.3
3	3	4	3	5	2	2	14*	13	14*	0.3
3	3	4	3	5	4	2	14	15	16*	0.3
3	3	4	3	7	1	2	16*	12	13	0.5
3	3	4	3	7	2	2	16*	13	14	0.5
3	3	4	3	7	4	2	16*	15	16*	0.4
3	3	4	3	10	1	2	19*	12	13	0.3
3	3	4	3	10	2	2	19*	13	14	0.3
3	3	4	3	10	4	2	19*	15	16	0.3
3	3	4	4	5	1	2	14*	13	14*	0.1
3	3	4	4	5	2	2	14	14	15*	0.1
3	3	4	4	5	4	2	14	16	17*	0.1
3	3	4	4	7	1	2	16	13	14	0.1
3	3	4	4	7	2	2	16	14	15	0.1
3	3	4	4	7	4	2	16	16	17	0.1
3	3	4	4	10	1	2	19	13	14	0.1
3	3	4	4	10	2	2	19*	14	15	0.1
3	3	4	4	10	4	2	19*	16	17	0.1

Clearly, the major drawback of this method is that every path in the project must be identified. However, it is very hard to identify all the paths if there are hundreds or thousands of activities in a project

5.5.2 Fuzzy PERT

Fuzzy PERT applies to problems where the duration of each task is an ill-known parameter, the set of more or less possible values of which is modeled by a fuzzy interval. The same algorithm as for deterministic cases is sometimes used in the fuzzy case the only difference being the use of fuzzy arithmetic instead of classical arithmetic

The basic idea of fuzzy PERT is first to evaluate the fuzzy interval containing the more or less possible values of the earliest starting time of each task by means of a forward recursion

Fuzzy PERT compute the possible values of the earliest starting dates by means of a forward recursion procedure comparable to the one used in classical CPM problems. Unfortunately there are still failures when to compute the possible values of the latest starting dates As soon as the latest starting date of the last task is set to its earliest date, the backward recursion issued from classical CPM is not sound if durations are described by means of fuzzy intervals thus preventing an accurate determination of the slack times and the criticality of the tasks

5 5 3 Comparison FNET versus Monte Carlo

As previously shown when the backward pass is performed in network scheduling, where activity durations are fuzzy numbers unrealistic accumulations of uncertainty might be created

Lorterapong and Moselhi overcome this problem by performing a complete fuzzy network analysis (FNET) In this analysis they perform the forward pass calculations by using the traditional fuzzy operations in order to compute the fuzzy early times of activities For the backward pass the researchers assumed that the right spread of fuzzy late times are at least as uncertain as their respective fuzzy early times

The researchers made a comparison between two schedules: one schedule created by using FNET and the other schedule created by assessing uncertainty using Monte Carlo simulation. The results are shown in Table 5-11 (Lorterapong, Moselhi 1996).

The final fuzzy project duration was found to be (52, 66 66 78) days. The interpretation of this fuzzy project duration is as follows

Duration can be approximately 66 days, with a definite minimum time of 52 days and a definite maximum completion time of 78 days

Table 5-5 FNET versus Monte Carlo

	Early Start		Early Finish		Late Start		Late Finish		TOTAL FLOAT			
										FNET		
Activity (1)	MC[a] mean (2)	FNET mode (3)	MC[a] mean (4)	FNET mode (5)	MC[a] mean (6)	FNET modes (7)	MC[a] mean (8)	FNET modes (9)	MC[a] mean (10)	TF (11)	PM (12)	AI (13)
1	0.00	0	0.00	0	0.04	0	0.04	0	0.00	0.00	0.96	0.53
2	0.00	0	11.03	11	0.04	0	11.07	11	0.00	0.00	0.46	0.35
3	0.00	0	11.18	12	2.06	0	14.06	16	3.96	2.00	1.00	0.36
4	11.03	11	18.00	18	11.07	11	14.64	16	0.04	0.36	1.09	0.55
5	14.04	14	31.06	31	34.08	18	31.20	32	0.02	0.00	1.00	0.91
6	31.08	31	48.05	48	31.64	31	48.03	48	0.57	2.00	1.00	0.95
7	31.08	31	35.17	35	32.39	31	34.31	33	1.26	0.67	0.92	0.93
8	48.05	48	50.05	50	48.63	48	50.62	50	0.57	1.56	0.96	0.93
9	31.08	35	42.09	42	34.35	33	42.34	42	1.26	0.67	0.93	0.93
10	48.08	50	54.08	55	50.61	50	50.23	55	0.51	0.00	0.06	0.73
11	43.06	43	48.06	48	61.30	69	65.28	66	19.25	21.00	0.14	0.00
12	42.04	42	48.00	48	43.34	42	55.29	55	1.26	0.67	0.92	0.92
13	34.68	35	42.67	43	57.38	57	69.28	69	3.60	3.06	0.85	0.79
14	54.66	55	60.75	61	55.20	55	61.20	61	0.58	0.00	0.96	0.95
15	60.75	61	64.75	65	61.20	61	65.28	65	0.38	0.00	0.30	0.93
16	54.66	56	64.02	64	58.20	58	65.28	66	1.51	0.67	0.72	0.72
17	64.75	66	64.75	64	65.28	66	65.28	66	0.38	0.00	0.30	0.95

Note: Project duration duration using Monte Carlo simulation, mean = 65.28 days, standard deviation = 1.98. Project duration duration using FNET (52, 66, 66, 78) days.

[a] Monte Carlo simulation.

The average project duration based on 5 000 iterations in the Monte Carlo simulation was 65.28 days with a standard deviation of 1 98 days. The percent deviation of the fuzzy mode from the probabilistic mean was +1 1%.

In conclusion the new fuzzy network scheduling method definitely rivals Monte Carlo simulation. The calculations in a fuzzy network schedule can be characterized as being very direct much simpler than in Monte Carlo simulations and definitely more transparent. By contrast Monte Carlo is much more difficult to follow due to the complexity of probability distributions.

5.6 Uncertainty Assessment of Project Duration Using Fuzzy Sets

5.6.1 Methodology for Modelling Construction Project Duration

In previous chapters a multitude of uncertain factors that affect the duration of construction activities and finally the project duration were listed and analyzed. It was also proved that it is quite difficult to quantify and to accurately incorporate the influence of uncertain factors in the duration estimate

In practice to determine project duration, contractors traditionally use the following model

PPD = PSD + TAU

Where PPD = predicted project duration

PSD = project duration under standard conditions

TAU = time allowances for uncertain conditions

The accuracy of this model depends on the availability of historical data and on the subjective judgment of the estimators. These practices do not guarantee a consistent estimate due to the lack of a binding mechanism that relates the present case to past patterns

The fuzzy model that will be used to predict project duration by considering the influence of multiple uncertain factors is presented in Figure 5-7 (Boussabaine, 2001) In this model the time influencing factors are considered as fuzzy consequences (numbers) to reflect their uncertainty and their effect on project duration The effect associated with each time influencing factor will be represented by three intervals

- High effect
- Average effect
- Low effect

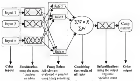

Input 1
Input 2
Input n
Rule 1
Rule 2
Rule m
$\frac{\sum W \times X}{\sum W}$
Crisp output
Crisp inputs
Fuzzification using the input linguistic variables
Fuzzy Rules: All rules are evaluated in parallel using fuzzy reasoning
Combining the results of all rules
Defuzzification: using the output linguistic variable terms
Crisp output

Figure 5-9 Fuzzy model of project duration

These effects can be determined on basis of variability reflected in the historical data that contractors experience in past projects and also the judgments of experts with relevant experience and know how The intervals are then used to construct the membership functions of the time influencing factors

The time allowed for uncertain conditions will be computed as a point or a crisp value and not as interval values The effect of the time influencing factors will be defuzzified by transferring it into a crisp value that represents the fuzzy number of time allowances

5 6 2 Selecting the Input Variables

The selection of the variables to be considered for assessing uncertainty to the duration of transportation construction projects is based on the normalized nominal range sensitivity analysis performed in Chapter 4 on the data provided by FDOT The analysis helped identify and rank the factors that have a higher significant contribution to the increase of original contract duration.

The assessment methodology will be divided into the three categories of transportation projects as already classified in the previous chapter short term project, medium term projects and long terms projects For each category the influence of the first five ranked factors will be considered

5 6.3 Fuzzy Inference Procedure

The computerized tool used to realize the fuzzy inference procedure was MATLAB® MATLAB® and companion toolboxes provide an environment for technical computing applications The Fuzzy Logic Toolbox extends the MATLAB environment to support the design of fuzzy logic based systems.

The MATLAB Fuzzy Toolbox provides a graphical user interface for defining the fuzzy controller (Figure 5 10) First the user defines inputs and outputs then the preferred types of membership functions can be chosen from a list and can be parameterized Various methods for AND OR implication, aggregation and defuzzification can be selected from pull-down menus. It is also possible to specify a m-file containing a user programmed method Finally the fuzzy rules can be edited in the Rule Viewer

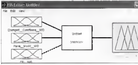


Figure 5-10 MATLAB FIS editor

The system structure identifies the fuzzy logic inference flow from the input variables to the output variable. The fuzzy inference takes place in rule blocks which contain the linguistic control rules. The output of these rule blocks is also a linguistic variable. The defuzzification method translates them into real values which is the predicted increase in project duration.

Table 5-6 lists all linguistic variables used in this system and their term names.

Table 5-6 Linguistic variables

Variable Name	Linguistic Terms
Weather	Favorable Adequate Unfavorable
Plans Modification (WO)	None Some Many
Plans Modification (SA)	None Some Many
Changed Conditions (WO)	Known, Fairly Known, Unknown
Changed Conditions (SA)	Known, Fairly Known Unknown
CEI (WO)	Positive Usual Negative
CEI (SA)	Positive Usual Negative
Utility Delays (SA)	Known, Fairly Known, Unknown
Duration Increase	Small Medium High

The properties of the variables considered to be most influential on the project durations are listed in Table 5-7. These properties were established by summarizing the data gathered in the tables from Appendix C and Appendix D. The unit used to analyze the input variables was in percentages of each variable's days over original contract duration days. The lower (MIN) and upper (MAX) variance bound are given.

Table 5-7 Base variables

Variable	Unit	MIN	MAX
Weather	% of Original Duration	0	82.20
Plans Modification (WO)	% of Original Duration	0	321.82
Plans Modification (SA)	% of Original Duration	-14.68	158.00
Change Conditions (WO)	% of Original Duration	0	76.47
Changed Conditions (SA)	% of Original Duration	0	110.28
CEI (WO)	% of Original Duration	11.00	123.33
CEI (SA)	% of Original Duration	-15.38	76.36
Utility Delays (SA)	% of Original Duration	0	34.69
% Duration Increase	% of Original Duration	0.67	345.45

The model is using the IF-THEN rules which contain the control strategy for the duration of the fuzzy logic system. Each rule block confines all rules for the same context. The context is defined by the same input and output variables of the rules. The IF rule describes the situation for which the rules are designed while the THEN rule describes the response of the fuzzy system estimated duration increase in this situation.

Table 5-8 shows the rule blocks used to establish the influence of the input variables weather, plans modifications (SA), and changed conditions (WO).

Table 5-8 Rule block

IF			THEN
Weather	Plans Modifications (SA)	Changed Conditions (WO)	Duration Increase
Favorable	None	Known	Small
Adequate	None	Known	Medium
Unfavorable	None	Known	High
Favorable	Some	Known	Medium
Adequate	Some	Known	Medium
Unfavorable	Some	Known	High
Favorable	Many	Known	Medium
Adequate	Many	Known	Medium
Unfavorable	Many	Known	High
Favorable	None	Fairly Known	Small
Adequate	None	Fairly Known	Small
Unfavorable	None	Fairly Known	Medium
Favorable	Some	Fairly Known	Small
Adequate	Some	Fairly Known	Medium
Unfavorable	Some	Fairly Known	Medium
Favorable	Many	Fairly Known	Medium
Adequate	Many	Fairly Known	Medium
Unfavorable	Many	Fairly Known	High
Favorable	None	Unknown	Medium
Adequate	None	Unknown	Medium
Unfavorable	None	Unknown	High
Favorable	Some	Unknown	Medium
Adequate	Some	Unknown	High
Unfavorable	Some	Unknown	High
Favorable	Many	Unknown	Medium
Adequate	Many	Unknown	High
Unfavorable	Many	Unknown	High

The properties of the variables for the short term projects are given in Table 5-9. For each input variable as well as for the output variable we insert into the system the lower (MIN) and the upper (MAX) bound of variation.

Table 5-9 Base variables (OCD = 1-3 months)

Variable	Unit	MIN	MAX
Weather	% of Original Duration	0	82.20
Plans Modification (WO)	% of Original Duration	0	321.82
Plans Modification (SA)	% of Original Duration	0	158.00
Change Conditions (WO)	% of Original Duration	0	76.47
Changed Conditions (SA)	% of Original Duration	0	49.28
CEI (WO)	% of Original Duration	0	123.33
CEI (SA)	% of Original Duration	0	29.09
Utility Delays (SA)	% of Original Duration	0	0
% Duration Increase	% of Original Duration	1.11	345.45
% Duration Increase	% of Original Duration	0.67	230.00

Table 5-10 contains the variation data for input and output variables for the medium term projects while Table 5-11 shows the variables for the long term projects.

Table 5-10 Base variables (OCD = 3 mo – 1 year)

Variable	Unit	MIN	MAX
Weather	% of Original Duration	0	69.10
Plans Modification (WO)	% of Original Duration	0	69.44
Plans Modification (SA)	% of Original Duration	0	52.73
Change Conditions (WO)	% of Original Duration	0	72.44
Changed Conditions (SA)	% of Original Duration	-1.33	110.28
CEI (WO)	% of Original Duration	-1.00	64.31
CEI (SA)	% of Original Duration	5.56	76.36
Utility Delays (SA)	% of Original Duration	0	34.22

The influence of the input variables on the duration increase was visualized using the Surface Viewer tool provided by the fuzzy toolbox in MATLAB. The three dimensional curves that represent the mapping from each two input variables (e.g. weather days and plans modifications) to the output variable (duration increase) are presented in Appendix F. The combinations of input variables are visualized for each of the three types of construction projects as classified in the previous chapter.

Table 5-11. Base variables (OCD > 1 year)

Variable	Unit	MIN	MAX
Weather	% of Original Duration	0	68.4
Plans Modification (WO)	% of Original Duration	0	13.01
Plans Modification (SA)	% of Original Duration	-14.68	81.03
Change Conditions (WO)	% of Original Duration	0	34.68
Changed Conditions (SA)	% of Original Duration	0	50.98
CEI (WO)	% of Original Duration	-11.00	29.72
CEI (SA)	% of Original Duration	-15.38	60
Utility Delays (SA)	% of Original Duration	0	34.69
% Duration Increase	% of Original Duration	1.83	134.59

An analysis of the influence of the input variables on project duration reveals the following:

- Both for short and medium term projects weather and changed conditions combined can contribute significantly to the increase of the project duration, by almost doubling it.
- Plans modifications in combination with changed conditions might not contribute to the fluctuation of project duration if both are known or fairly known. Their combined influence becomes dramatically when there are many plans modifications and the changed conditions were completely unknown. The effect on project duration is still a little smaller than the case when any of these variables is combined with the weather variable.
- The effect of the weather variable in combination with CEI can be almost negligible unless both are at the higher upper bound, case when than effect might be the increase of the project duration up to almost 170%.
- For long term projects the weather variable in combination with any other time extension factors has considerable effect on the project duration.

5.7 Procedure for Uncertainty Assessment

The proposed procedure for uncertainty assessment into scheduling repetitive construction processes was thought as a series of steps that embed the findings from the pervious analysis. The procedure is presented in Figure 5-11.

5.7.1 Define Type of Project

The first step consists in determining if the project can be classified as a short term, medium term or long term project. This step is necessary in order to determine which input variables will be considered in the assessment procedure as having the most powerful influence on the original project duration

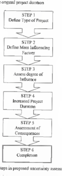

STEP 1
Define Type of Project
STEP 2
Define Main Influencing Factors
STEP 3
Assess degree of Influence
STEP 4
Increased Project Duration
STEP 5
Assessment of Consequences
STEP 6
Completion

Figure 5-11 Steps in proposed uncertainty assessment procedure

5.7.2 Define Main Influencing Factors

In this step the uncertain factors that have been proved to have an influence of more than 5% over the original project duration will be itemized based on the ranking established in Chapter 4 The claims (SA) will not be incorporated into this step because of the lack of detailed information on the nature of these claims.

5.7.3 Assess Degree of Influence

During this step to each uncertain input variable will be assessed a degree of influence based on expert opinion elicitation. Expert opinion elicitation is recommended because it is considered that the empirical knowledge possessed by experts accumulates information experts have acquired from experience. Also it is assumed that the experts' empirical knowledge in specific domains has some kind of statistic data behind it.

From studies of how well calibrated are expert judgments about uncertainty it appears that the most frequent problem encountered is overconfidence (Frey, 1998).

Other heuristic approaches most commonly used by people in making judgments are: the availability or easiness with which people can recall the past instances of an outcome, the representativeness of the set of numbers they use, the anchoring which makes use of a natural starting point as the basis for making adjustments, and last but not least human motivation. In order to avoid the biases that can be introduced at this level of estimate, the degree of fuzziness of the experts' empirical knowledge should be considered. This kind of analysis does not make the subject of this research, but is strongly recommended for the future.

In this particular research experts have already available data on the extreme high and low values of each input variable aspect that helped to overcome the typical problem of overconfidence. The expert will be asked only to estimate the central values of the variables. The output will be determined by using the 3_D figures created with the Surface Viewer tool in MATLAB and included in Appendix F.

In order to combine the influence of different input variables into a single output value, different methods can be used.

5.7.3.1 Minimum value method

The minimum outcome value for each input variable can be computed as follows

$$MIN_{variable} = \min_{i=1}^{n}(variable)$$

The minimum values can then be normalized using their total in order to obtain their normal outcome as $NORM\_MIN_{plan\ modifications\ (SA)} = \frac{\min_{plan\ modification\ (SA)}}{\sum \min_{variable}}$

5.7.3.2 Maximum value method

The maximum outcome value for each input variable can be computed as follows:

$$MAX_{variable} = \max_{i=1}^{n}(variable)$$

The maximum values can then be normalized using their total in order to obtain their normal outcome as $NORM\_MAX_{plan\ modifications\ (SA)} = \frac{\max_{plan\ modification\ (SA)}}{\sum \max_{variable}}$

5.7.3.3 Weighted arithmetic average

The weighted arithmetic mean for the outcome can be computed as follows.

$$Wighted\_Arithmetic\_Mean = \left(\frac{\sum W x X}{\sum W}\right)$$

5.7.4 Increased Project Duration

In this step of the assessment procedure the findings from the previous step will be used to calculate the increase of original contract duration of the project Minimum increase and maximum increase of original project duration can be quantified based on an optimistic and a pessimistic approach

The result of this step will offer valuable information both for the owner and the contractors on the expected range of percentage of increase in project duration

5 7 5 Assessment of Consequences

After having established the range of increase for the project duration, dollar values should be attached to the contract days In this step the nature of the project and contract provisions have to be considered

For example for an incentive/disincentive type of contract, the number of time units (days, months etc) the original contract duration is expected to increase will be multiplied with the value of the disincentives as stipulated into the contract clauses

This step constitutes a valuable control tool both for the owner and the contractor by integrating time and cost aspects of the project

5 7 6 Completion

The final step in the assessment procedure finalizes the analysis by creating a report that presents the results of the assessment. The report should also include suggestions for actions that should be taken in order to reduce the possibility of increase in original contract duration.

5.8 Fuzzy Linear Scheduling Algorithm

5 8 1 Basic Constraining Rules

As already revealed in Chapter 3, there is a solution to criticality problems within linear schedules This solution assesses a deterministic duration or a deterministic productivity to the activities the linear schedule

In order to consider inherent uncertainties that affect activity production rates and consecutively activity durations a fuzzy approach is proposed The approach will assess fuzzy numbers to the factors in equation 2 1, focusing on the uncertainties inserted into the production rate

In order to create a proper scheduling algorithm for multiple repetitive construction processes there are two basic rules (Figure 5 12) that have to be considered

Rule1 When the production rate of an activity is greater than the unit production rate of the preceding activity the two activities will tend to converge as the number of units increase

And

Rule2 When the production rate of an activity is smaller than the production rate of the proceeding activity the two production lines will tend to diverge as the number of units increases

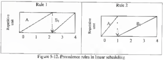


Figure 5-12. Precedence rules in linear scheduling

5.8.2. Algorithm for Calculating Activity End Point

Let us consider a typical construction activity like guardrail (identified by GR) with a known starting point This point is a control point $GRep_0$ while the activity will be also a controlling activity The duration of the activity on a single location (sector or unit) is determined by the unit production rate (P^{h}_{ij}) of the activity ij which is assumed to be unknown.

The unit production rate can be represented as a triangular fuzzy number $P^{h}_{ij} = (P_m, P_a, P_M)$, where P_m is the minimum possible value P_a is the average value and P_M is the maximum possible value of the productivity The minimum, average and maximum values are taken from FDOT guidelines for establishing contract durations The values are as follow P_m = 200 LF/WKDAYS, P_o = 400 LF/WKDAYS, P_M = 1500 LF/WKDAYS

The triangular fuzzy production rate for guardrail will be P_{01} = (200, 400, 1500) as shown in Figure 5-13

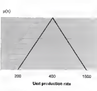


Figure 5-13 Fuzzy production rate for guardrail

Consider the other factors (quantity, crew size, and dividing factor) involved in the calculation of the activity duration (equation 3-1) as deterministic and having fixed numerical values

In conformity to the fuzzy addition the duration of the activity 01 performed in the space unit 1 will be also a fuzzy triangular number $T^1_{01} = (T_m, T_o, T_M)$ For the easiness of the calculations, we consider a quantity of 1,000 LF The duration of the activity will be the new fuzzy number T^1_{01} = (0.6, 2.5, 5.0) By convention, for a starting controlling activity the starting (control) point will be at time zero cp_0 = (0, 0, 0).

The ending point of the activity will be $ep_1 = cp_0 \oplus T_{1j}$ Based on previous presented fuzzy algebraic operations with fuzzy numbers we obtain the end point of the activity guardrail $GRep^1_{11} = GRcp_0 \oplus^7 Tij = (0.6, 2.5, 5)$ The algorithm representing this first assumption is depicted in Figure 5-14

```
①    Input: Starting Point Activity $A^K_{ij}$ $sp_{ij} = (0, 0, 0)$
     Let Production = $P^K_{ij} = (m^K, a^K, M^K)$
     Let Quantity = $Q_{ij}$

②    Calculate Duration $T^K_{ij} = (Q^K_{ij}/M^K, Q^K_{ij}/a^K, Q^K_{ij}/m^K)$

③    Deliver Ending Point $ep^K_{ij} = sp^K_{ij} \oplus T^K_{ij}$
```

Figure 5-14 Algorithm for calculating end point

5.8.3 Algorithm for Calculating Elements of Next Segment Activity

The next assumption is that the same activity will take place on the second repetitive unit, in the same circumstances (quantity, productivity, duration, and all influencing factors are constant for each repetitive unit) The ending point of the activity (ep^k_{1j}) in the first unit (K = 1) becomes the starting point of the activity (sp^{k+1}_{2j}) in the second unit (K+1 = 2).

The ending point of the activity guardrail in the second unit ($GRep_2$) will be calculated as a sum of the two fuzzy numbers which represent the control point or the start of the activity in the first unit ($GRcp_1$) and the duration of the activity in the first unit (T^K_{1j}) The sign ⊕ represents the fuzzy addition $GRep_2 = GRcp_1 \oplus T^K_{1j} = (1.2, 5, 10)$.

The algorithm used to generate the next segment of a repetitive activity is shown in Figure 5-15

---

[7] The signs ⊕ and ⊖ are used for fuzzy addition and subtraction respectively

```
①   Input Activity $A^{K}_{1j}$ End Point $ep^{K}_{1j} = (m^{K}_{1j}, a^{K}_{1j}, M^{K}_{1j})$
    Let Production = $P^{K}_{2j} = (P^{K}_{2m}, P^{K}_{2a}, P^{K}_{2M})$
    Let Quantity = $Q^{K+1}_{2j}$

②   Setup Starting Point Activity $A^{K+1}_{2j}$ $sp^{K+1}_{2j} = (m^{K+1}_{2j}, a^{K+1}_{2j}, M^{K+1}_{2j}) = ep^{K}_{1j}$
    $= (m^{K}_{1j}, a^{K}_{1j}, M^{K}_{1j})$

③   Calculate Duration $T^{K+1}_{1j} = (Q^{K+1}_{1j}/P^{K+1}_{1M}, Q^{K+1}_{1j}/P^{K+1}_{1a}, Q^{K+1}_{1j}/P^{K+1}_{1m})$

④   Deliver Ending Point $ep^{K+1}_{1j} = sp^{K}_{1j} \oplus T^{K+1}_{2j}$
```

Figure 5-15 Algorithm to generate the next segment of a repetitive activity

5.8.4 Algorithm for implementing Rule 1 and Rule 2

The next algorithm (Figure 5-16) refers to the situations described in Rule 1 and Rule 2

```
①   Input Activity $A^{K}_{1j}$ End Point $ep^{K}_{j} = (m^{K}_{j}, a^{K}_{j}, M^{K}_{j})$
    Let Production = $P^{K}_{1j} = (P^{K}_{m}, P^{K}_{a}, P^{K}_{M})$
    Let Quantity = $Q^{K}_{1j}$

②   IF $P^{K}_{2j} > P^{K}_{1j}$   GO TO STEP ⑤

    IF $P^{K}_{2j} \le P^{K}_{1j}$   GO TO STEP ⑧

③   Let Buffer @ K= n $B^{K}_{12} = 1/P^{K}_{2j} = (1/P^{K}_{M}, 1/P^{K}_{a}, 1/P^{K}_{m})$
    Let Buffer @ K=1 $B^{K}_{12} = (B^{K}_{m}, B^{K}_{a}, B^{K}_{M})$

④   Calculate Duration @ K = n $T^{K}_{2j} = (Q^{n}_{2j}/P^{n}_{M}, Q^{K+n}_{2j}/P^{K+n}_{a}, Q^{K+n}_{2j}/P^{K+n}_{m})$

⑤   Calculate Ending Point @ K = K + 1 $ep^{K}_{2j} = ep^{K}_{1j} \oplus B^{K}_{12}$

⑥   Calculate Starting Point @K = K + 1 $sp^{K}_{2j} = ep^{K}_{2j} \ominus T^{K}_{1j}$

⑦   IF $sp^{K}_{2j} \ge sp^{K}_{1j}$   GO TO STEP ②

⑧   Calculate Starting Point @ K=1 $sp^{K}_{2j} = sp^{K}_{1j} \oplus B^{K}_{12}$

⑨   Calculate Starting Point @ K=1 $sp^{K}_{2j} = sp^{K}_{1j} \oplus B^{K}_{12}$
```

Figure 5 16 Algorithm for upward pass and downward pass

In order to avoid the situation when two activities with different production rates might converge as the number of repetitive units increases, a time lag or buffer was introduced. The value of the time lag has in its turn some uncertainties incorporated, and can be represented as a fuzzy number. The algorithm performs an upward pass and also a downward pass depending on the rhythm of the activities.

5.9 Summary and Conclusions

In this chapter the basics of the fuzzy sets theory and the main mathematical operations with fuzzy sets are presented. Two examples of the application of fuzzy sets in project scheduling are offered: a network scheduling using fuzzy CPM and a fuzzy PERT. The methods prove to be quite easy and intuitive despite a major drawback which is that every path in the project must be identified. Definitely for projects having hundreds or even thousands of activities it becomes very hard to identify all the paths.

In order to assess uncertainty to transportation construction projects the variables identified and ranked in the previous chapter were used as input variables for a typical fuzzy model. The novelty consists in the fact that this type of analysis is custom made for transportation construction projects. Another significant aspect of this analysis is that it uses as input variables parameters whose influence on contract duration has been recorded and documented by state agencies based on historical data. A combined impact of uncertain factors is already inserted into these parameters facilitating the quantification process. The identified impact of these factors will be further used in a new proposed uncertainty assessment procedure.

After having established the effect of different uncertain factors on the project duration, in order to implement uncertainty into linear scheduling techniques three simple fuzzy algorithms were developed. The algorithms make use of the fuzzy approach customized to the requirements and capabilities of the linear scheduling method

CHAPTER 6
VERIFICATION AND VALIDATION THROUGH A CASE STUDY

6.1 Introduction

After compiling the various uncertain variables into the scheduling system the next step is the verification and validation of the uncertainty assessment procedure in scheduling multiple repetitive construction processes.

The objective of the uncertainty assessment validation is to examine its practical applicability for the particular case of a repetitive construction project. The results of the validation will be utilized for further enhancement of the emergent scheduling system.

The case study used to validate the developed procedure is the Tri-Rail Segment 5 project. Information necessary for this project is provided. Following that, the scheduling problems generated by using deterministic durations were analyzed.

The final step was to incorporate uncertainty factors into the scheduling process by using the fuzzy sets theory in the tentative to develop a realistic schedule estimate.

6.2. The Tri-Rail Case Study

6.2.1 Project Description

Before presenting the assessment of the uncertainty and its consequences on the total project duration, this section will provide background material on the Tri-Rail project. This material is adapted from the Tri-County Commuter Rail Authority (further called Tri-Rail) press releases on the Tri-Rail's web page (Tri-Rail 2003).

The Tri-Rail operates a 71.7-mile regional transportation system connecting Palm Beach, Broward and Miami-Dade counties in South Florida. The improvements planned by Tri-Rail are designated to significantly increase the service reliability of commuter rail in the rail corridor owned by the Florida Department of Transportation (FDOT).

Tri-Rail project includes the construction of a second mainline track the rehabilitation of the signal system and improvements of stations and parking system

Segment 5 is Tri-Rail's project name for the final phase of double tracking the remaining, approximately 45 miles of the South Florida Rail Corridor (SFRC) When completed in 2005 the project will enable Tri-Rail to run 20-minute headways (time between trains) during morning and afternoon rush hour

The Double Track Corridor Improvement Program Segment 5 project (Figure 6-1) consists of the following main works:

- Installation of new track
- Upgrades to existing track
- Construction and rehabilitation of bridges
- Renovation of nine existing stations
- Construction of one new station in Boca Raton
- Demolition of existing station in Boca Raton
- Upgrades to signal-safety systems
- Acquisition of new locomotives and cab cars
- Enhancements to grade crossings
- Upgrades to passenger information systems

To date 9 6 miles of the Double Track Corridor Improvement Project have been completed, including a station at Miami International Airport, which is planned to be a part of the proposed Miami Intermodal Center FDOT, in conjunction with Tri Rail, is arranging to assume the dispatching and maintenance operations in the corridor from CSX Transportation (CSXT) in 2005

Total cost for the project is estimated at $327 million (escalated dollars), with a Section 5309 New Starts commitment of $110 5 million

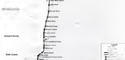


Figure 6-1 Tri-Rail project map

6.2.2 Projects Status

The Tri-Rail system was created in 1989 as a traffic mitigation project during the State's widening of Interstate 95. Environmental requirements for the Tri-County Commuter Rail improvements were satisfied with categorical exclusions.

The Tri-Rail double-track corridor improvement project will be implemented in five segments. Segment I, an 8.14-mile portion between Pompano Beach and Broward Boulevard began in Spring 1995 and was completed in April 1997. Phase II, a 1.5-mile southern extension terminating at New Miami International Airport Station, adjacent to the site of the proposed Miami Intermodal Center, was completed in Spring 1998. Phase III, a 6.9-mile extension from south of the proposed Boca Raton/Glades Road Station to south of the Pompano Beach Station, began in March 1998 and was completed in July 2000.

Tri-Rail signed a Full Funding Grant Agreement (FFGA) with FTA in June 2000 to implement Segment 5 of the Double Track Corridor Improvement Program. Segment 5 is scheduled for completion in March 2005. TEA-21 Section 3030(a) authorizes the Ft.

Lauderdale-West Palm Beach-Miami Tri-County Commuter Rail for final design and construction Through FY 2001, Congress has appropriated $25.66 million in Section 5309 New Starts funds for the project (Table 6-1), with an additional $54.26 million appropriated to the project, but not included in the scope of the FFGA.

Table 6-1: Tri-Rail funding details

Proposed Source of Funds	Total Funding ($million)	Appropriations to Date
Federal		
5309 New Starts FFGA Commitment	$110.5	($25.66 million appropriated through FY 2001)
5307 Urbanized Area Formula Funds	$14.9	
5309 Guideway Modernization	$19.3	
Flexible Funds	$57.2	
State		
Florida DOT	$69.9	
Local		
Private Sector Financing	$55.2	
TOTAL[1]	$327.0	

6.2.3 Managerial Issues with Impact on Project Performance

The managerial issues presented in this paragraph were researched during an internship completed at the Tri Rail project for a period of three months in 2003

Another relevant source of information was the lessons learned program[2] developed in assistance with the Federal Transit Administration (FTA). Project Management Oversight Program (PMOP) contractors, transit properties and FTA regional engineers. The lessons learned program is an integral part of the PMOP and was developed for the benefit of all other parties that may embark on building transit projects in the future (Federal Transit Administration, 2003)

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[1] Totals may not add due to rounding. An additional $54.26 million was appropriated to the project in prior years but was not included in the FFGA scope.

[2] Lessons are developed by a PMO contractor and coordinated with the transit property to insure that the lesson is portrayed with the proper perspective

In the Tri Rail project there is more than one agency with responsibility for project delivery This aspect created many problems with the coordination of the management team Each party involved in the project had different needs that sometimes were quite contradictory and not easy to satisfy

The problems of this project started from the design stage Because important issues like constructability and operational issues were not adequately addressed during the design the effect was a five month project delay from the start and many change orders

The relationship between the owner of the right-of-way (Florida DOT) and the transit agency (Tri-Rail) was another key factor that influenced the project schedule At the outset of the Phase I Double Tracking project, reporting relationships review and approval authority, and contract administration procedures were not fully defined Other complications were created by the existing agreements with the operating railroad (CSXT) which has both dispatching as well as some construction responsibilities

Preparations for major milestone events were inadequate resulting in major impacts on operations. The design did not adequately address staging To accommodate cut-in of new sections of track the temporary track configurations could not accommodate normal revenue operations. The time frame to complete several key activities was also underestimated which further impaired on time perfomance

Tri-Rail's contract operator has also undertaken the rail construction work on the project This may have facilitated an early start to the project and offered the opportunity for the operator who is also the contractor to resolve problems more effectively than two separate organizations.

The contract terms did not adequately address the conflict between the operator (whose performance is measured based on on-time performance), and the contractor (who wants to avoid production delays due to train operations). This conflict created a potential for claims to be made by the construction forces when impacted by changes in operations. On the other side, on time performance suffered due to the contractor's desire to meet estimated production rates.

6.2.4 Tri-Rail Project Scheduling

The Tri-Rail project schedule was primarily developed for tracking the scope of services. The schedule also served for invoicing purpose. The project contract for Phase I was a lump sum. The invoice amount (earned value) was based on the percent complete of the deliverables. The level of detail of the schedule was required to be as detailed as possible in order to quantify the amount of work accomplished.

The schedule was subdivided into five categories, each containing several deliverables, as follows:

- Project management
- Project control
- Engineering and design
- Design and build procurement
- Community outreach

The following steps were taken in Tri-Rail schedule development (Wis, Carter, 2002).

- STEP 1: Develop a draft preliminary schedule by project controls
- STEP 2: Forward the draft schedule to the project manager for review
- STEP 3: Incorporate comments into the preliminary project schedule
- STEP 4: Discuss and review the preliminary project schedule with the task managers during weekly meetings
- STEP 5: Develop a draft project schedule
- STEP 6: Forward the draft project schedule to the task managers for final review
- STEP 7: Submit schedule to TRI RAIL for review

- STEP 8 Incorporate Tri-Rail comments into the project schedule
- STEP 9 Submit schedule for approval
- STEP 10 Establish the baseline schedule[1]

From the above steps it can be noticed that the development of the Tri-Rail schedule required extensive coordination efforts among parties involved Figure 6-2 shows a flow chart of the schedule development

A compromise between the schedule and invoicing had to be made because at the time when the schedule was developed it was not easy to obtain detail activity information and despite the fact that the project was at its early stages the client wanted to have the schedule completed as early as possible In order to meet the client's requirements the management cost loaded only the major activities that are deliverables This decision facilitated once again the potential for disputes between the client and the prime consultant and between the prime consultant and the sub-consultants The disputes were mainly on the percent of work completion.

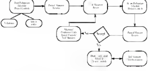

Figure 6-2 Tri-Rail schedule development

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[1] The baseline schedule served as the milestone tracking as well as the measurement of project progress

Even if the nature of the project classifies it as a repetitive type of project, the project was scheduled by using Primavera P3. The project has almost 3 000 activities, which would have made linear scheduling method unusable at this level of complexity, due to the lack of proper marketable software.

The critical path showed up on the maintenance/layover facility portion of the project, and the near critical activity is the design/build procurement. As the project progressed, uncertainties were encountered, resulting in a delay of the project.

One aspect that created scheduling problems was that the project scope and conditions have not been very clear from the beginning. Because of this reason utility relocations could not be developed to an advanced level without additional major investment.

Another problem was created by the drainage design which could not be verified completely in order to bring the project to a 30 percent level of design.

The delay on the critical path item, maintenance/layover facility, resulted primarily from public opposition to the preferred location of the facility. Despite the cumulated efforts of the owner, consultants and other parties involved, the public opposition forced the project management to take the decision to remove the facility from its initial design/build procurement scope. This decision changed the initial non-critical nature of other activities which became critical. The conclusion of the project control team was that in the future variances for activities with float should also be tracked closely.

Because of the complexity of the project, and the interests of multiple participants, coordination between parties was not an easy task. Furthermore, it was difficult to come to an agreement pertaining to the territorial issues.

6.2.5 Tri-Rail Project Schedule Update

The submitting of the required schedule update information by the sub-consultants along with their individual invoice packages did not created any particular problems, mainly due to the involvement of the project controls engineers which were in constant contact with sub-consultants. The project controls engineers made use of their own judgment and understanding of the project to update and forecast the project schedule.

A variance report was created (Figure 6-3) based on the information in the updated schedule (Win, Carter 2002). In the report each deliverable was evaluated for variance and the identified reasons for delay were recorded. Most of the delayed activities were not on the critical path, but it was necessary to be identified because they could become critical and affect the project duration.

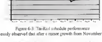

Figure 6-3 Tri-Rail schedule performance

It can be easily observed that after a minor growth from November 1999 which was the starting date of the Tri-Rail project, the schedule performance index begun to decline dramatically to April 2000. In June 2000 the index started to recover again.

6.3 Verification of the Uncertainty Assessment Procedure

The objective of this phase is to assess uncertainties to the project schedule and decide if the project progress reflects the embedded variations.

The verification is performed by a review of the individual steps in the proposed procedure Once this is completed a holistic verification of the proposed procedure will be applied.

6.3.1 Define Type of Project

In this step the type of project will be identified according to the classification used during the fuzzy analysis The Tri-Rail Segment 5 project has an original contract duration of five years, which classifies as a long term type of transportation contraction projects

6.3.2 Define Main Influencing Factors

Establishing the uncertainty factors that can have a significant impact on the project duration is made by using the ranking matrix for uncertain parameters.

The following factors are considered as being most influential for this project, in the order of their rank as calculated in Chapter 4

1. Plans modifications (SA)
2. CEI (SA)
3. Changed conditions ((SA)
4. Weather
5. Utility delays (SA)

Three experts directly involved in the scheduling of the Tri Rail project were interviewed in order to attach linguistic variables to the input factors. One of the experts was the main scheduler for the contractor of the construction works another is the owner's representative, and the third is with a consulting firm that worked with the contractor's team at the accelerating schedule

6.3.3 Assess Degree of Influence

In this step the degree of influence the uncertainty factors was computed

For this purpose the three dimensional curves provided by the fuzzy inference system were be used. The assessment is synthesized in a matrix format (Table 6-2) which captures the influence of each pair of two variables. The degree of influence of each variable was estimated based on the Surface Viewer graphs as offered by MATLAB and also using the input of the three experts. The common agreement was to use average values for the degree of influence assessment.

Table 6-2. Influence assessment matrix

Variables / Influence (%)		Plans modifications	CEI	Changed conditions	Weather	Utility delays
		40%	25%	17%	30%	15%
Plans modifications	40%	27%	51%	65%	68%	48%
CEI	25%	51%	16%	26%	37%	64%
Changed conditions	17%	65%	26%	41%	33%	48%
Weather	30%	68%	37%	33%	24%	39%
Utility delays	15%	48%	64%	48%	39%	58%
MIN		27%	16%	26%	24%	39%
NORM_MIN		20.45%	12.12%	19.69%	18.18%	29.54%
MAX		68%	64%	65%	68%	58%
NORM_MAX		21.05%	19.81%	20.12%	21.05%	17.95%
Weight		0.30	0.20	0.40	0.20	0.50

The weights assessed to the output represent the degree of belief of the three experts in the possibility for a specific output to be obtained. It can be observed that the weights do not add up to the unit, neither have to be different for various input variables. The values of the weights considered represent the average of the weights proposed by each of the three experts.

The weighted arithmetic average for the most optimistic approach (MIN) was calculated to be 28.75% showing the minimum combined influence of all input variables considered.

The weighted arithmetic average for the most pessimistic approach (MAX) was estimated to be 63.6% showing the maximum combined influence of all input variables considered.

The optimistic approach (MIN) shows an increase of 28.8% while the pessimistic approach (MAX) will consider an increase of original duration of 63.6%

$$\left(\frac{\sum WxX}{\sum W}\right)_{MIN} = \left(\frac{0.3*27\%+0.2*16\%+0.4*26\%+0.2*24\%+0.5*39\%}{1.6}\right) = 28.8\%$$

$$\left(\frac{\sum WxX}{\sum W}\right)_{MAX} = \left(\frac{0.3*68\%+0.2*64\%+0.4*65\%+0.2*68\%+0.5*58\%}{1.6}\right) = 63.6\%$$

The similar calculations were performed for both the normalized maximum and normalized maximum output

$$\left(\frac{\sum WxX}{\sum W}\right)_{MIN}^{NORM} = \left(\frac{0.3*20\%+0.2*12\%+0.4*20\%+0.2*18\%+0.5*29\%}{1.6}\right) = 21.8\%$$

$$\left(\frac{\sum WxX}{\sum W}\right)_{MAX}^{NORM} = \left(\frac{0.3*21\%+0.2*20\%+0.4*20\%+0.2*21\%+0.5*18\%}{1.6}\right) = 19.68\%$$

The results show that when we consider the normalized output, there is a switch between the most pessimistic and the most optimistic approaches. The calculations give us a percentage of increase of 21.8% when the normalized minimum output is considered, while the increase calculated for the normalized maximum output is lower, 19.68% respectively.

6.3.4 Increased Project Duration

The increased project duration will be determined by embedding the influences of the input variables into the original contract duration

Increased Project Duration = Original Contract Duration + % Duration Increase

$MIN_{\text{Increased Project Duration}} = 51 + (51) \times (0.288) = 51 + 15 = 66$ months

$MAX_{\text{Increased Project Duration}} = 51 + (51) \times (0.636) = 51 + 32 = 83$ months

$NORM\ MIN_{\text{Increased Project Duration}} = 51 + (51)(0.218) = 51 + 11 = 62$ month

$NORM\ MAX_{\text{Increased Project Duration}} = 51 + (51)(0.1968) = 51 + 10 = 61$ month

6.3.5 Assessment of Consequences

In conclusion due to the influences considered for the different uncertain factors the project duration is expected to increase with minimum of 10 months up to almost 3 years in the worst case scenario. In order to interpret the results the feedback of the three experts was requested. At the time of this part of the analysis only two of them were available. Their input was used in order to assess degree of beliefs to the estimated increase of original project duration. The results are presented in figure 6-4

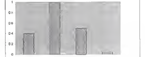

Figure 6-4 Degrees of belief for expected duration increase

6.3.6 Completion/Validation

After all steps have been completed the final results were compared with the real life situation. Up to date information indicates that after a first delay of 5 months of the Tri-Rail project (in 2002), at this time (October 2003) the construction is expected to be delayed by 9 more months, which results in a total of 14 months delay from the original contracted duration.

Comparing the existing information with the estimated increase obtained by using the fuzzy set approach, we can conclude that the fuzzy estimation is relatively close to the actual state of the project.

CHAPTER 7
CONCLUSIONS AND FUTURE RESEARCH

7.1 General Comments

This research effort represents a systematic study of the different problems and variables associated with scheduling multiple repetitive construction projects. An extensive survey and a thorough literature review were undertaken to examine different construction scheduling methods used in the United States in transportation construction projects.

It was easily noticeable that one of the oldest and most appropriate scheduling methods for this particular type of construction projects (Linear Scheduling Method) is far behind in terms of popularity and usability compared to the other commonly used methods (Critical Path Method, PERT, and bar charts). At the same time the research showed that Linear Scheduling Method (LSM) has great potential and valuable visual capabilities that cannot be attained by the other methods. Furthermore, several governmental publications are calling for more research and study of this method.

The above findings were the driving force behind the searching for solutions to the drawbacks of LSM. As the second main complain of practitioners was the lack of uncertainty assessment into this method (the first complain was found to be the lack of computer software to make Linear Scheduling a usable scheduling tool), the research goal became to assess uncertainties into LSM.

The fuzzy set theory provides better alternatives to probability when used for characterizing different kinds of uncertainties within the same problem and also conformity with experts' thinking as part of formal elicitation principles it was decided that this will be the most suitable method to use in assessing uncertainty to LSM

7.2 Conclusions

7.2.1 Current Practices in Scheduling Repetitive Construction Processes

From a survey among State Highway Agencies (SHAs) was found that the most common used methods for scheduling are the Critical Path Method (CPM) and the bar charts Past research revealed that for the particular case of repetitive construction projects the Linear Scheduling Method (LSM) has many capabilities when compared with the other two methods These capabilities can be effectively and efficiently used in planning and scheduling this particular type of multiple repetitive construction projects The lack of proper software and the need for a formal method to determine uncertainties in time completion seem to be the main drawbacks of LSM

7.2.2 Current Practices in Uncertainty Assessment

Various methods for assessing uncertainty in scheduling construction works were studied and the advantages and disadvantages of these methods were revealed. The major weakness found in the application of these methods was that they neglect to address the vagueness and imprecision already incorporated into the cognitive sources of the data used by these methods The fuzzy set theory was proved to be the only uncertainty assessment method that has the capability to process linguistic terms as used by experts thus allowing the quantification of expert knowledge in estimating and assessing uncertainty

7.2.3 Identification of Uncertain Factors in Construction

The fact that up to-date research has identified a vast list of variables that can constitute sources of risk for construction projects was uncovered through the literature review performed One of the problems found was the lack of consistency in handling the concepts of risk and uncertainty by various researchers It was also noticed that available data refers mainly to the field of building construction and there is no research to address the particularities of repetitive construction processes mainly those belonging to the transportation construction projects.

7.2.4 Data Collection Practices

The research revealed that the most common practice to identify uncertain variables that affect construction projects consist in surveys dispatched mainly among contractors There is little research to address the client or client's representative points of view The present research made use of data as already synthesized by the client of transportation construction projects which in U S are the various districts of transportation The advantages offered by this particular source of data is that it already incorporates factors which the client has formerly acknowledged as having important influences on the development of the construction project and on the construction schedule respectively

7.2.5 Uncertainty Assessment Procedure

The proposed assessment procedure has the ability of being a flexible tool that helps determine possible project durations for different combinations of the main uncertain construction factors The fuzzy approach used in developing this procedure has the capability to capture expert knowledge and insert it into the construction schedule The procedure is also tailored to the particularities of transportation construction projects in general and also to the client s terminology requirements and interests This application can help schedulers to consider uncertainty for various scheduling alternatives and make a decision for the most accurate project duration selection Because the input data used comes from different types of repetitive construction projects we consider that it already encloses the characteristics of all these types of projects and that it can be further used despite the particularities of each project

7.2.6 Conducting Expert Opinion Elicitation on the Influence of Input Variables

The degree of influence of each uncertain input variables considered in the uncertainty assessment procedure was based on expert opinion elicitation Expert schedulers' opinions were used in this research because of the detailed and deep knowledge accumulated from experience by these experts and also for the particularities of the statistic data assumed to subsist behind their knowledge Bias could be minimized by providing already processed data on the extreme high and low values of each input variable to the experts.

7.2.7 Validation of the Uncertainty Assessment Procedure

The uncertainty assessment procedure was validated on the Tri-Rail Segment 5 project case study The validation process had some weaknesses mainly due to the singularity of the case study used. Even if the Tri-Rail Segment 5 project is a complex and highly representative case for the repetitive construction projects, it is per se insufficient for validation purposes. Time and data availability restrictions were the main reason for using a single case study for validation Another aspect related to the validation process was that the Tri-Rail project is not yet finalized which enabled the researcher to compare estimated project duration with the final projects' duration Potential duration increases will be validated only after the completion of the Tri-Rail project.

7.3 Future Research

Even if in general terms the originally stated research objectives were satisfactorily accomplished there is always room for further improvement. The present section proposes some recommendations for future enhancement of the developed uncertainty assessment procedure and the fuzzy scheduling algorithms

7.3.1 Further Study of Terminology used in Risk and Uncertainty Research

The literature reviewed uncovered the fact that there is still a lot of confusion on the notions of risk and uncertainty which are used interchangeably much too often There is a definite and immediate need for researchers to use a common language in relation to the concepts of risk and uncertainty A dictionary for risk and uncertainty could offer a solution to this problem

7.3.2 Further Comparisons between Different Uncertainty Assessment Techniques

The further analysis of the subjects of risk and uncertainty revealed that uncertainty assessment techniques like Monte Carlo or stochastic simulation are preferred by researchers despite the fact that the assumptions made in order to use them do not conform with the origins of uncertainty Future research is needed in order to compare the outputs of different uncertainty assessment techniques and their degree of accuracy, particularly for the problem of scheduling under uncertainty

7 2.3 Improvement of the Uncertainty Assessment Procedure

The extensive literature reviewed suggests that integrating both construction costs and duration into the uncertainty assessment procedure would offer a more capable tool for measuring project's performance Also insertion of users needs and requirements into the procedure will dramatically improve the contractor's scheduling performances as well Future research is needed on how to estimate user costs and delays associated with construction project delays

7.2.4 Insertion of the Effect of Contracting Methods in Future Studies

The effect of innovative contracting techniques (A+B, incentives/disincentives, and lane rental) should also be studied in the future in relation to the best practices associated with project schedule management.

7.2.5 Development of Integrated Scheduling Models Based on Artificial Intelligence

The applicability and efficiency of using artificial intelligence (AI) techniques like genetic algorithms, simulated annealing, tabu search and neuro fuzzy models in scheduling multiple repetitive construction processes would be a future interesting investigation to perform. Additional linkages between these theories are required.

7.2.6 Further Study on Different Applications of the Developed Fuzzy Scheduling Algorithm

The fuzzy scheduling algorithm developed in this research was intended to be applied to different types of repetitive projects and scheduling techniques. Future research could aid in identifying appropriate schedule-management strategies, tactics, and implementation tools for each type of construction project.

7.2.7 Further Approaches of Expert Opinion Elicitation

The selection of the experts whose opinions will be requested for the uncertainty assessment procedure has to be carefully prepared. The number of experts to be used, as well as their years of experience with the particular area researched must be sensibly considered. Commonly, the expert-opinion elicitation process has the objective of achieving consensus on the degree of influence of different input variables and on the degrees of belief assigned to these variables. Disagreement among experts will create the need to weight their opinions for appropriateness and relevance.

APPENDIX A
STATE DOT SURVEY RESULTS

Table A-1. State DOT survey results

State Dept. Of Transportation	Reports using LSM		Reports Familiarity w/ LSM		
	Yes	No	Very	Somewhat	None
Alabama		X			X
Arizona		X			X
Arkansas		X			X
Arkansas					
California		X			X
Colorado		X		X	
Connecticut	X^{2}		XX		
Delaware		X		X	
Florida		X^{5}		X	
Georgia		X^{6}		X	
Hawaii		X			X
Idaho		X			X
Indiana		X			X
Iowa		X^{7}		X	
Kansas		X			X
Kentucky		X		X	
Louisiana		X			X
Maryland		X			X
Mississippi		X			X
Missouri		X			X
Montana		X			X
Nebraska		X^{3}			X
New Jersey		X		X	
New York		X		X	
Nevada		X		X	
North Carolina		X			X
North Dakota		X			X
Oregon		X^{3}			X
Pennsylvania		X^{3}			X
South Carolina		X			X
South Dakota		X			X
Texas	X^{2}		XX		
Utah		X^{4}			X
Vermont		X			X

Table A-1 (continued)

State Dept Of Transportation	Reports using LSM		Reports Familiarity w/ LSM		
	Yes	No	Very	Somewhat	None
Virginia	At contractors' option[9]		XX		
Washington		X			X
West Virginia		X			X
Wisconsin	Not Required[7]			X	

Notes

[1] Only 37 states as listed, responded to the survey

[2] Reports using claim analysis

[3] Reports using LSM, actually using Bar Charts/CPM

[4] Reports using LSM, actually using SureTrak

[5] Interested but wants better software has funded research with University of Florida

[6] Considering trial use with some projects

[7] Has funded research to develop specifications & software

[8] Was used by a contractor in a recent claim.

[9] Used by several contractors

APPENDIX B
ELEMENTS OF IGNORANCE IN KNOWLEDGE

Table B -1: Elements of ignorance

Level	Element	Definition/Description
6	Ignorance	The lack of knowledge
5	Conscious Ignorance	A self-ignorance that is recognized through reflection
	Blind Ignorance	The ignorance of self-ignorance (Not knowing that you don't know)
4	Inconsistency	Lacking of harmonious uniformity between things and parts due to wrong, conflicting or biased assignments
	Incompleteness	Incomplete or imperfect knowledge due to absence, unknowns and uncertainty
	Fallacy	A misconception resulting from incorrect reasoning
	Unknowable	Knowledge that is beyond and outside the ordinary range of human experience or understanding
	Irrelevance	The lack of a relation of something to the matter at hand
3	Confusion	A mistake that results from a wrongful substitution
	Conflict	Contradictory assignments or substitutions
	Inaccuracy	Errors, bias or distortion in degree
	Uncertainty	Incompleteness in knowledge as a result of deficiencies with acquired knowledge
	Unknowns	The becoming knowledge state versus the current knowledge state
	Absence	Incompleteness in kind
	Untopicality	Expert knowledge outside the range of common knowledge
	Taboo	Irrelevance reinforced both socially and culturally
	Undecidability	Unsolvable issues having no nominated value of true or false
2	Approximations	Some proven worst or average case bound on performance
	Likelihood	Appearance or probability of outcomes
	Ambiguity	Unclearness by virtue of having more than one outcome
1	Vagueness	Unclearness or fuzziness about the degree of belonging, or not to a set of notions of interest
	Coarseness	Approximating a crisp set by subsets of an underlying partition of the set's universe that would bound the set of interest
	Simplifications	Assumptions that make solutions tractable
	Randomness	Outcomes lacking predictability
	Sampling	The selection of a suitable sample for study
	Nonspecificity	Improperly defined outcomes
	Unspecificity	Outcomes or assignments that are not completely defined

APPENDIX C
FDOT TIME REPORT 2001

Table C-1 Project contract time data (FDOT)

District	Contract Number	Number of SAs	Original Contract Days	Present Contract Days	Days Used	Unused Days	Delinquent Days	Days Suspended	Time Extension	SA Days	Weather Days
01	19439	26	712	892	892	0	0	119	38	139	23
01	19492	15	270	548	239	9	0	59	126	22	23
01	19529	13	505	573	272	1	0	28	41	27	39
01	19744	11	828	1102	1107	-4	4	106	160	123	116
01	18740	4	180	274	274	0	0	0	0	94	0
01	19807	26	632	1156	1156	-10	10	16	95	426	41
01	19974	11	222	773	779	-6	6	12	197	41	76
01	20026	4	100	122	124	1	0	232	22	0	21
01	20072	1	62	114	114	0	0	142	49	0	1
01	20073	1	60	62	64	-2	2	140	2	0	1
01	20074	2	140	191	219	-28	28	106	11	40	11
01	20120	1	170	170	156	14	0	101	0	0	0
01	20228	12	590	210	218	-8	8	0	01	141	01
01	20230	3	292	214	214	0	0	40	3	6	3
01	20233	1	130	177	212	35	22	32	47	0	17
01	20334	1	150	190	225	22	33	86	40	0	2
01	20258	2	110	124	136	2	2	97	22	1	2
01	20260	2	200	270	382	13	13	15	66	4	7
01	20261	2	250	292	293	2	0	12	42	0	24
01	20223	2	290	489	472	14	0	0	199	0	199
01	20222	2	100	134	134	0	0	28	17	17	12
01	20422	22	640	908	907	1	0	7	52	216	52
01	20625	4	155	269	252	10	0	0	29	82	29
01	20672	2	212	262	284	22	22	42	47	0	41
01	20694	2	272	279	242	34	0	0	4	0	4
01	20729	4	110	170	170	0	0	0	2	28	2
01	20729	0	42	49	52	-6	6	0	4	0	4
01	20774	2	220	278	279	1	1	0	0	22	0
01	20772	10	400	325	320	2	2	0	0	75	0
01	20808	1	200	227	312	72	75	0	27	0	3
01	20828	0	100	132	132	0	0	0	22	0	2

Table C-1 (continued)

District	Contract Number	Number of SAs	Original Contract Days	Present Contract Days	Days Used	Unused Days	Delinquent Days	Days Suspended	Time Extension	SA Days	Weather Days
01	20829	1	30	32	32	0	0	0	2	0	2
01	20862	0	70	77	75	2	0	0	7	0	7
01	20863	2	120	86	85	1	0	0	7	-41	7
01	20894	4	390	416	403	13	0	0	41	15	26
01	20970	2	135	237	239	-2	2	0	37	65	37
01	20971	0	100	100	75	25	0	0	0	0	0
01	20972	2	70	73	69	4	0	0	3	0	3
01	20998	1	100	127	141	-14	14	0	27	0	5
01	21000	1	145	145	140	5	0	0	0	0	0
01	21002	1	60	72	72	0	0	0	6	6	0
01	21004	0	110	110	40	70	0	0	0	0	0
01	21620	1	145	150	150	0	0	0	11	-6	11
01	21648	0	40	40	36	4	0	0	0	0	0
01	21869	1	30	51	47	4	0	0	1	0	1
01	21141	2	150	163	110	53	0	0	13	0	13
01	21177	1	115	121	120	1	0	0	10	-4	10
01	21221	0	50	72	69	3	0	0	22	0	22
01	21228	0	30	37	37	0	0	0	7	0	7
01	21248	0	60	60	52	8	0	0	0	0	0
01	21321	0	40	40	35	5	0	0	0	0	0
01	21344	0	30	32	31	1	0	0	2	0	2
District 1 Totals			10850	13674	13651	23	258	1437	1714	1110	982
02	19248	8	395	535	534	1	0	113	138	2	80
02	19627	8	400	604	599	5	0	305	105	99	105
02	19673	2	100	117	90	27	0	75	17	0	17
02	19685	3	165	240	240	0	0	91	45	30	22
02	19755	11	295	434	434	0	0	168	51	88	51
02	19772	1	75	125	117	8	0	56	50	0	39
02	16812	11	295	434	434	0	0	75	68	71	68
02	19822	13	360	1188	1168	20	0	283	261	567	11
02	19826	5	676	714	714	0	0	313	38	0	38
02	20017	7	180	281	278	3	0	55	86	15	49
02	20077	0	45	45	38	7	0	0	0	0	0
02	20079	4	210	268	295	3	0	84	86	2	51
02	20268	12	400	427	417	10	0	243	6	21	50
02	20270	1	90	101	99	2	0	52	6	5	6
02	20295	3	225	271	269	2	0	64	24	22	24
02	20431	1	300	316	316	0	0	21	19	3	22
02	20433	8	330	669	673	-4	4	45	36	303	36

Table C-1 (continued)

District	Contract Number	Number of SAs	Original Contract Days	Present Contract Days	Days Used	Unused Days	Delinquent Days	Days Suspended	Time Extension	SA Days	Weather Days
02	20452	2	147	208	307	-99	99	90	23	28	17
02	20499	4	239	407	407	0	0	52	41	127	25
02	20500	2	149	240	264	24	24	181	99	8	12
02	20503	2	330	499	499	0	0	63	169	0	68
02	20540	1	225	217	222	-6	6	75	97	5	59
02	20580	6	260	280	269	11	0	128	20	10	18
02	20586	6	420	562	562	0	0	17	32	110	22
02	20636	1	420	299	298	0	0	0	21	0	21
02	20640	3	255	527	521	-4	4	0	272	0	29
02	20723	4	500	254	254	0	0	0	18	0	18
02	20734	2	180	154	128	16	0	0	4	30	4
02	20736	1	45	59	59	0	0	177	14	0	0
02	20758	2	270	247	236	11	0	186	14	0	14
02	20782	1	150	192	180	12	0	0	42	0	4
02	20792	4	420	452	454	29	0	30	73	0	73
02	20811	6	500	500	478	22	0	0	0	0	0
02	20812	1	210	332	221	11	0	0	122	0	41
02	20831	2	240	321	313	8	0	0	61	28	32
02	20834	2	120	207	204	3	0	0	87	0	27
02	20839	2	210	251	327	24	0	0	85	56	79
02	20866	1	90	91	78	12	0	0	1	0	1
02	20867	2	207	258	270	12	12	27	46	5	46
02	20868	2	260	260	291	69	0	0	0	0	0
02	20896	2	210	216	212	4	0	0	6	0	6
02	20898	2	180	246	249	-3	2	19	26	60	19
02	20899	1	270	412	411	2	0	0	143	0	22
02	20937	5	299	483	386	97	0	0	66	27	59
02	20940	4	290	472	468	4	0	0	177	5	121
02	20966	2	97	150	199	0	0	0	60	0	0
02	20975	2	120	238	238	0	0	0	44	24	5
02	20980	1	150	150	119	31	0	0	0	0	0
02	21006	2	210	273	265	8	0	0	60	17	6
02	21008	1	180	194	176	18	0	0	16	0	14
02	21040	3	150	251	251	0	0	0	56	45	25
02	21028	2	150	203	203	0	0	0	52	0	12
02	21029	5	166	160	121	25	0	0	0	0	0
02	21030	1	120	134	101	2	0	0	4	20	4
02	21052	2	180	192	172	21	0	0	12	0	12
02	21071	2	150	164	164	0	0	0	26	22	18

Table C-1 (continued)

District	Contract Number	Number of SAs	Original Contract Days	Present Contract Days	Days Used	Unused Days	Delinquent Days	Days Suspended	Time Extension	SA Days	Weather Days
02	51074	0	60	148	147	1	0	0	88	0	14
02	51076	5	180	516	516	0	0	0	56	0	38
02	51118	0	50	50	16	14	0	0	0	0	0
02	51147	5	510	516	199	17	0	0	6	0	6
02	51149	1	45	40	40	0	0	0	5	8	5
02	51179	5	150	212	130	82	0	0	62	0	56
02	21181	0	60	94	94	0	0	0	34	0	17
02	51183	1	60	22	22	0	0	0	0	-38	0
02	51284	1	60	75	75	0	0	0	0	-15	0
02	21285	0	45	55	50	5	0	0	7	0	4
District 5 Totals			14404	19177	18475	594	155	2046	3367	1660	1695
03	18468	10	521	747	743	4	0	0	105	123	105
02	18777	11	570	868	866	5	0	1	515	165	553
02	19103	1	165	577	452	175	175	0	115	0	115
02	19408	1	145	157	157	0	0	79	12	0	15
03	19623	3	110	119	149	30	30	67	9	0	0
03	19706	8	553	909	922	-13	13	5	165	191	134
03	19796	5	540	575	570	5	0	7	235	0	255
03	19847	6	375	555	550	5	0	57	160	0	126
03	19929	5	150	205	254	-59	59	0	55	0	50
05	19956	5	568	456	502	-46	46	15	140	0	115
05	19986	2	200	261	281	-20	20	10	61	0	26
03	20124	12	785	956	948	8	0	16	142	59	142
03	20158	1	300	385	379	5	0	7	65	0	76
05	20194	10	660	734	665	69	0	41	74	0	72
05	20241	3	590	689	895	-504	204	15	49	50	49
05	20305	11	690	725	685	40	0	19	14	1	14
05	20308	1	120	130	124	6	0	75	10	0	10
05	20310	1	145	161	160	1	0	30	16	0	16
05	50343	1	60	105	105	0	0	2	15	0	15
02	50370	4	174	225	280	-55	55	50	58	15	19
02	20380	5	230	275	335	-62	62	6	23	20	23
02	50406	3	450	495	489	4	0	5	73	30	71
03	20461	4	445	624	723	-99	99	4	150	59	120
03	20507	1	510	568	504	4	0	0	98	0	98
03	20589	5	320	395	386	9	0	4	52	43	35
03	20590	5	306	555	543	15	0	4	209	46	146
03	20594	1	460	561	561	0	0	0	101	0	51
03	20595	8	555	555	560	46	0	4	50	0	30

Table C.1 (continued)

District	Contract Number	Number of SAs	Original Contract Days	Present Contract Days	Days Used	Unused Days	Delinquent Days	Days Suspended	Time Extension	SA Days	Weather Days
03	20397	2	374	403	379	24	0	0	29	0	29
03	20643	1	33	343	243	0	0	0	190	0	13
03	20676	2	303	379	277	3	0	0	74	0	11
03	20703	0	378	360	376	-16	16	0	82	0	70
03	20779	1	173	240	338	3	0	0	65	0	31
03	20843	1	75	116	116	0	0	0	41	0	41
03	30874	0	75	137	134	3	0	0	62	0	21
03	20904	2	40	47	47	0	0	0	1	6	1
03	20947	1	160	136	139	-3	3	0	34	2	25
03	20981	0	120	144	143	-1	1	0	24	0	18
03	20983	0	173	249	249	0	0	0	74	0	66
03	20984	1	73	83	81	2	0	0	8	0	8
03	20983	0	70	80	77	3	0	0	10	0	10
03	20987	0	80	90	93	-3	3	0	10	0	3
03	31013	0	340	399	399	0	0	0	59	0	36
03	31014	0	93	154	143	9	0	0	59	0	39
03	31031	1	85	105	104	1	0	0	20	0	16
03	21032	1	45	53	50	3	0	0	8	0	8
03	21067	3	200	258	250	8	0	0	34	34	31
03	21082	0	70	93	93	2	0	0	25	0	10
03	21084	1	265	250	239	11	0	0	10	25	10
03	21086	0	75	82	83	3	3	0	7	0	7
03	31088	0	133	162	162	0	0	0	27	0	6
03	31121	1	144	233	231	3	0	0	89	0	89
03	31174	0	60	68	66	3	0	0	8	0	8
03	31203	1	33	31	31	0	0	0	16	0	2
District 3 Totals			13069	19379	17846	-467	750	495	3565	745	2778
04	19117	11	343	1036	1042	-6	0	884	281	230	32
04	19383	3	310	479	473	4	0	233	169	0	9
04	19999	13	975	1013	852	160	0	33	31	6	31
04	20004	15	608	804	804	0	0	0	102	94	12
04	20033	4	140	198	196	3	0	403	58	0	17
04	20060	16	310	667	667	0	0	0	64	93	36
04	20101	16	760	875	873	0	0	12	76	19	62
04	20130	2	133	313	313	0	0	131	73	7	8
04	20202	13	660	816	816	0	0	114	111	45	54
04	20248	17	376	849	843	4	0	32	83	190	69
04	20410	5	310	313	313	0	0	58	36	167	14
04	20467	4	430	433	344	111	0	0	25	10	10

Table C-1 (continued)

District	Contract Number	Number of SAs	Original Contract Days	Present Contract Days	Days Used	Unused Days	Delinquent Days	Days Suspended	Time Extension	SA Days	Weather Days
04	20468	2	206	257	255	2	0	31	57	0	14
04	20469	8	375	254	553	1	0	150	4	175	4
04	20470	5	195	305	301	4	0	199	7	103	7
04	20494	0	110	143	143	0	0	0	23	0	14
04	20558	1	280	342	242	0	0	19	85	0	4
04	20681	0	220	220	188	24	0	0	0	0	0
04	20742	2	122	142	142	0	0	0	2	0	1
04	20770	2	200	259	229	0	0	0	29	30	29
04	20782	9	220	294	293	1	0	0	97	7	7
04	20784	1	200	200	198	2	0	0	0	0	0
04	20785	3	167	170	170	0	0	0	3	0	3
04	20786	2	160	218	218	0	0	0	14	44	3
04	20846	4	272	322	324	1	0	0	23	30	13
04	20847	8	290	360	328	2	0	0	23	37	32
04	20850	0	120	151	120	1	0	0	1	0	1
04	20878	2	340	354	304	20	0	0	14	0	14
04	20879	5	102	124	123	1	0	0	8	11	8
04	20912	2	172	190	190	0	0	0	13	2	5
04	20947	2	190	253	222	0	0	0	22	0	9
04	21018	0	22	68	68	0	0	0	18	0	1
04	21090	0	90	90	90	0	0	0	0	0	0
04	21128	0	100	110	110	0	0	0	10	0	10
04	21129	0	100	100	100	0	0	0	0	0	0
04	21187	0	100	103	84	19	0	0	2	0	2
04	21188	1	100	104	97	7	0	0	4	0	4
04	21189	1	90	104	128	28	0	0	74	0	74
04	21252	1	90	60	66	24	0	0	0	0	0
District 4 Totals			10655	13635	13163	472	0	2323	1672	1208	643
05	19788	4	440	275	212	80	0	28	125	10	105
05	20136	11	720	847	854	7	7	27	23	94	28
02	20205	4	280	400	400	0	0	18	40	30	28
05	20212	3	782	821	851	0	0	64	66	0	51
05	20214	13	822	977	977	0	0	0	48	78	22
02	20472	4	182	221	210	1	0	23	48	0	41
05	20521	7	120	278	272	1	0	60	66	80	22
02	20667	9	300	380	380	0	0	7	19	81	17
02	20613	8	442	628	628	0	0	117	28	127	22
05	20657	3	240	332	472	147	141	0	80	0	23

Table C-1 (continued)

District	Contract Number	Number of SAs	Original Contract Days	Present Contract Days	Days Used	Unused Days	Delinquent Days	Days Suspended	Time Extension	SA Days	Weather Days
05	20660	14	885	928	642	286	0	0	32	10	32
05	20744	2	400	469	460	9	0	0	69	0	40
05	20793	0	210	264	262	2	0	0	54	0	36
05	20794	1	180	234	234	0	0	0	27	27	10
02	20749	2	50	94	102	-8	8	0	41	3	9
02	20824	2	200	287	287	0	0	0	64	23	41
02	20882	2	420	461	369	92	0	0	21	0	21
02	20885	1	90	121	284	-162	163	0	10	21	0
02	20916	2	119	205	205	0	0	0	46	40	24
02	20926	0	150	234	234	0	0	0	64	0	62
05	20927	0	290	297	292	2	0	0	7	0	7
02	20991	0	45	69	69	0	0	0	24	0	12
02	21019	0	100	138	128	10	0	0	28	0	20
02	21022	0	100	130	127	3	0	0	30	0	18
05	21641	0	120	147	142	2	0	0	27	0	8
02	21062	0	60	67	62	5	0	0	7	0	6
02	21066	0	40	40	29	1	0	0	0	0	0
05	21094	1	152	228	228	0	0	0	58	12	39
05	21095	1	142	224	217	7	0	0	79	0	42
05	21100	2	142	201	201	0	0	0	56	0	21
05	21129	0	30	100	114	-14	14	0	30	0	0
05	21122	0	130	210	210	0	0	0	80	0	80
05	21136	0	82	158	158	0	0	0	73	0	8
05	21160	0	90	103	102	1	0	0	13	0	13
02	21162	1	80	121	120	1	0	0	20	21	20
02	21172	0	70	70	68	2	0	0	0	0	0
05	21172	2	170	193	192	1	0	0	23	0	23
02	21193	0	108	120	117	2	0	0	20	0	14
02	21194	0	160	194	192	1	0	0	34	0	24
02	21202	1	80	99	111	-12	12	0	19	0	19
02	21222	0	60	70	68	2	0	0	10	0	10
05	21223	0	100	115	112	0	0	0	15	0	15
05	21240	1	60	77	76	1	0	0	17	0	17
05	21247	0	60	89	92	3	3	0	29	0	22
05	21262	0	140	159	158	1	0	0	19	0	19
05	21213	0	90	101	101	0	0	0	11	0	11
05	21228	0	52	73	72	0	0	0	18	0	2
05	21342	0	30	34	34	0	0	0	4	0	1

Table C 1 (continued)

District	Contract Number	Number of SAs	Original Contract Days	Present Contract Days	Days Used	Unused Days	Delinquent Days	Days Suspended	Time Extension	SA Days	Weather Days
05	21346	0	65	86	86	0	0	0	1	0	1
05	21435	0	25	25	24	1	0	0	0	0	0
District 5 Totals			10233	12612	12462	150	348	392	1771	608	1180
06	19831	2	500	535	400	125	0	48	35	0	35
06	19861	4	550	610	610	0	0	17	60	0	60
06	19862	21	825	1000	1000	0	0	75	107	58	16
06	20023	4	400	447	956	509	509	59	22	75	17
06	20031	2	220	289	343	-54	54	32	29	129	29
06	20196	2	745	718	712	6	0	0	22	-60	5
06	20662	8	600	611	592	19	0	0	11	0	11
06	20747	4	180	237	237	0	0	0	57	0	38
06	20825	2	406	501	460	41	0	0	101	0	100
06	20886	2	70	72	72	0	0	0	2	0	2
06	20919	0	214	235	201	34	0	0	21	0	20
06	20920	1	75	110	108	2	0	0	25	0	24
06	20921	1	220	276	275	1	0	0	56	0	56
06	20922	1	109	103	89	14	0	0	3	0	2
06	20953	0	240	248	236	12	0	0	8	0	8
06	20957	0	406	408	299	109	0	0	8	0	8
06	21062	2	280	295	268	27	0	0	15	0	15
06	21063	3	200	262	125	128	0	0	63	0	18
06	21096	1	250	282	230	52	0	0	32	0	32
06	21097	1	280	286	257	29	0	0	16	0	16
06	21131	1	250	253	250	2	0	0	2	0	2
06	21106	1	270	274	249	25	0	0	5	-61	5
06	21197	2	100	116	116	0	0	0	16	0	0
06	21272	1	180	182	147	26	0	0	3	0	2
District 6 Totals			7549	8408	8272	129	563	233	741	111	524
07	19365	19	890	1048	1017	21	0	449	96	62	64
07	19125	25	775	1594	1796	202	202	62	47	772	47
07	19299	9	715	914	1036	122	122	128	205	-6	105
07	19421	9	540	701	693	8	0	200	154	7	86
07	19572	10	510	806	814	-8	8	225	292	4	66
07	19947	5	545	545	525	20	0	21	0	0	0
07	20192	1	115	115	117	2	2	0	0	0	0
07	20287	2	600	621	495	126	0	56	15	6	14
07	20392	1	58	58	259	209	209	0	0	0	0
07	20486	2	120	167	167	0	0	0	47	0	2

Table C-1 (continued)

District	Contract Number	Number of SAs	Original Contract Days	Present Contract Days	Days Used	Unused Days	Delinquent Days	Days Suspended	Time Extension Days	SA Days	Weather Days
07	20530	13	465	662	664	-2	2	63	155	42	53
07	20572	4	565	412	411	1	0	17	9	38	9
07	20621	4	555	408	409	0	0	38	54	0	14
07	20693	2	400	453	435	18	0	43	53	0	1
07	20725	0	105	105	103	2	0	0	0	0	0
07	20806	1	175	209	209	0	0	0	34	0	28
07	20821	14	225	477	467	10	0	0	175	77	12
07	20856	1	160	328	570	-42	42	0	81	87	25
07	20858	2	50	133	133	0	0	0	4	79	4
07	20859	0	540	617	593	24	0	0	57	0	10
07	20995	2	155	165	163	2	0	0	15	15	15
07	20997	1	69	129	127	2	0	0	26	34	26
07	21021	0	200	257	254	5	0	0	57	0	29
07	21200	0	30	37	36	1	0	0	7	0	7
07	21220	1	45	52	49	3	0	0	7	0	7
07	21311	1	10	10	9	1	0	0	0	0	0
07	21341	0	45	54	54	0	0	0	9	0	9
07	21345	0	40	40	40	0	0	0	0	0	0
District 7 Totals			8094	10910	11245	-335	587	1304	1309	1217	636
08	19284	19	1055	1311	1310	1	0	0	2	274	0
08	19726	18	661	1059	1059	0	0	0	5	575	0
08	19852	10	1315	1449	1447	2	0	0	53	81	0
08	19868	21	486	776	775	1	0	0	2	288	0
08	20002	13	491	708	708	0	0	0	5	212	5
08	20185	14	297	695	695	0	0	0	182	116	15
08	20322	4	261	388	386	2	2	0	123	0	7
08	20620	5	510	524	524	0	0	0	14	0	14
08	20865	1	212	577	563	14	0	6	120	45	8
08	20857	1	303	314	164	150	0	0	11	0	11
District 8 Totals			5671	7577	7411	166	2	8	517	1389	60

APPENDIX D
TIME EXTENSIONS DUE TO WORK ORDERS

Table D-1 Time extensions due to work orders

District	Contract Number	Number of SAs	Changed Conditions Work Orders		Plans Modifications Work Orders		Specifications Modifications Work Orders		Value Engineering Work Orders		Partnering Work Orders		CEI Action/Inaction Work Orders		Minor Changes Work Orders		Defective Materials Work Orders		Weather Related Damage Work Orders		Claims Work Orders		Utility Delays Work Orders		Invalid Reason Codes Work Orders		Totals Work Orders	
			Time Ext Days	SA Days	Time Ext Days	SA Days	Time Ext Days	SA Days	Time Ext Days	SA Days	Time Ext Days	SA Days	Time Ext Days	SA Days	Time Ext Days	SA Days	Time Ext Days	SA Days	Time Ext Days	SA Days	Time Ext Days	SA Days	Time Ext Days	SA Days	Time Ext Days	SA Days	Time Ext Days	SA Days
01	19439	26	13	25	2	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	103	0	0	15	130
01	19409	13	54	7	12	15	0	0	0	0	0	0	10	0	0	0	0	0	0	0	0	0	0	0	11	0	122	22
01	19579	12	2	2	0	25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	27
01	19744	11	39	0	0	36	0	0	0	0	0	0	5	0	0	81	0	0	0	0	0	0	0	0	0	0	44	123
01	19790	4	0	0	0	94	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	94
01	19807	56	33	5	0	24	0	0	0	0	0	0	[illegible]	384	0	16	0	0	0	0	0	0	0	0	0	0	54	426
01	19976	11	0	0	0	39	0	0	0	0	0	0	121	0	0	0	0	0	0	2	0	0	0	0	0	0	121	41
01	20036	4	22	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	24	0
01	20072	1	0	0	0	0	0	0	0	0	0	0	48	0	0	0	0	0	0	0	0	0	0	0	0	0	48	0
01	20073	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
01	20074	2	0	0	0	0	0	0	0	0	0	0	0	40	0	0	0	0	0	0	0	0	0	0	0	0	0	40
01	20150	1	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	3
01	20220	12	0	0	0	0	0	0	0	0	0	0	0	141	0	0	0	0	0	0	0	0	0	0	0	0	0	141
01	20229	3	0	0	0	0	0	0	0	0	0	0	0	6	0	0	0	0	0	0	0	0	0	0	0	0	0	6
01	20232	1	0	0	0	0	0	0	0	0	0	0	20	0	0	0	0	0	0	0	0	0	0	0	0	0	20	0
01	20234	1	0	0	0	0	0	0	0	0	0	0	35	0	0	0	0	0	0	0	0	0	0	0	0	0	35	0
01	20250	2	21	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	21	1
01	20300	3	0	0	0	4	0	0	0	0	0	0	50	0	0	0	0	0	0	0	0	0	0	0	0	0	50	4
01	20301	2	0	0	0	0	0	0	0	0	0	0	21	0	0	0	0	0	0	0	0	0	0	0	0	0	21	0
01	20333	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
01	20335	2	0	0	0	17	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	2	17
01	20482	22	0	0	0	0	0	0	0	0	0	0	0	-6	0	0	0	0	0	0	0	0	0	222	0	0	0	216
01	20616	4	0	0	0	67	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	10	0	0	0	85
01	20672	2	0	0	0	3	0	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	4	3
01	20684	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
01	20720	4	0	0	0	58	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	58
01	20750	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
01	20774	5	0	15	0	0	0	0	0	0	0	0	0	7	0	0	0	0	0	0	0	0	0	0	0	0	0	22
01	20775	16	0	0	0	0	0	0	0	0	0	0	0	25	0	0	0	0	0	0	0	0	0	0	0	0	0	25

Table D-1 (continued)

District	Contract Number	Number of SAs	Changed Conditions Work Orders		Plans Modification Work Orders		Specification Modification Work Orders		Value Engineering Work Orders		Partnering Work Orders		CEI Action/Inaction Work Orders		Minor Changes Work Orders		Defective Materials Work Orders		Weather Related Damage Work Orders		Claims Work Orders		Utility Delays Work Orders		Invalid Reason Codes Work Orders		Totals Work Orders	
			Time Ext Days	SA Days	Time Ext Days	SA Days	Time Ext Days	SA Days	Time Ext Days	SA Days	Time Ext Days	SA Days	Time Ext Days	SA Days	Time Ext Days	SA Days	Time Ext Days	SA Days	Time Ext Days	SA Days	Time Ext Days	SA Days	Time Ext Days	SA Days	Time Ext Days	SA Days	Time Ext Days	SA Days
01	20808	1	0	2	0	0	0	0	0	0	0	0	22	0	0	0	0	0	0	0	0	0	0	0	0	0	33	2
01	20828	0	0	0	0	0	0	0	0	0	0	0	29	0	0	0	0	0	0	0	0	0	0	0	0	0	29	0
01	20829	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
01	20862	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
01	20863	2	0	-41	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-41
01	20891	4	0	0	0	7	7	0	0	15	0	0	0	0	0	0	0	0	0	0	0	0	13	0	0	0	13	13
01	20970	2	0	0	0	0	0	0	0	0	0	0	0	65	0	0	0	0	0	0	0	0	0	0	0	0	0	65
01	20971	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
01	20972	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
01	20998	1	0	2	0	0	0	0	0	0	0	0	17	0	0	0	0	0	0	3	0	0	0	0	0	0	17	5
01	21000	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
01	21002	1	0	0	0	12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	12
01	21004	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
01	21026	1	0	0	0	0	0	0	0	0	0	0	0	-6	0	0	0	0	0	0	0	0	0	0	0	0	0	-6
01	21040	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
01	21099	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
01	21141	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
01	21177	1	0	0	0	0	0	0	0	0	0	0	0	-4	0	0	0	0	0	0	0	0	0	0	0	0	0	-4
01	21221	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
01	21228	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
01	21248	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
01	21321	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
01	21344	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
District 1 Totals			248	27	14	107	0	0	0	15	0	0	422	257	0	97	0	0	0	41	0	0	13	342	31	0	785	1127
02	19748	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	1	0	0	0	0	0	58	2	58	2
02	19827	8	0	94	0	7	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	99
02	19673	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
02	19685	3	0	0	23	30	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	23	31
02	19755	11	0	3	0	40	0	45	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	88

Table D-1 (continued)

District	Contract Number	Number of SAs	Changed Conditions Work Orders		Plans Modification Work Orders		Specification Modification Work Orders		Value Engineering Work Orders		Partnering Work Orders		CEI Activities Work Orders		Minor Changes Work Orders		Defective Materials Work Orders		Weather Related Damage Work Orders		Claims Work Orders		Utility Delays Work Orders		Invalid Reason Codes Work Orders		Totals Work Orders	
			Time Ext Days	SA Days	Time Ext Days	SA Days	Time Ext Days	SA Days	Time Ext Days	SA Days	Time Ext Days	SA Days	Time Ext Days	SA Days	Time Ext Days	SA Days	Time Ext Days	SA Days	Time Ext Days	SA Days	Time Ext Days	SA Days	Time Ext Days	SA Days	Time Ext Days	SA Days	Time Ext Days	SA Days
02	19772	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	20	0	20	0
02	19847	11	0	47	0	24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	71
02	19822	13	0	247	250	120	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	250	367
02	19825	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
02	20017	7	0	0	0	0	0	0	0	0	0	0	37	15	0	0	0	0	0	0	0	0	0	0	0	0	37	15
02	20027	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
02	20079	4	0	2	0	0	0	0	0	0	0	0	35	0	0	0	0	0	0	0	0	0	0	0	0	0	35	2
02	20248	12	0	7	0	-4	0	0	0	0	0	0	-44	18	0	0	0	0	0	0	0	0	0	0	0	0	-44	21
02	20270	1	0	0	0	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5
02	20395	3	0	0	0	22	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	22
02	20431	1	0	0	0	0	0	0	0	0	0	0	3	3	0	0	0	0	0	0	0	0	0	0	0	0	3	3
02	20433	8	0	0	0	51	0	0	0	0	0	0	0	252	0	0	0	0	0	0	0	0	0	0	0	0	0	303
02	20453	3	0	0	0	44	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	44
02	20499	4	0	0	0	73	0	0	0	0	0	0	0	60	0	0	0	0	0	0	0	0	0	0	0	0	0	133
02	20500	2	0	0	0	4	0	0	0	0	0	0	74	0	0	0	0	0	0	0	0	0	0	0	0	0	74	4
02	20503	2	60	0	0	0	0	0	0	0	0	0	41	0	0	0	0	0	0	0	0	0	0	0	0	0	101	0
02	20540	1	0	0	0	0	0	0	0	0	0	0	0	33	0	0	0	0	0	0	0	0	0	0	0	0	0	33
02	20581	8	0	0	0	10	0	0	0	0	0	0	0	12	0	0	0	0	0	0	0	0	0	0	0	0	0	22
02	20586	6	0	26	0	0	0	0	0	0	0	0	0	84	0	0	0	0	0	0	0	0	0	0	0	0	0	110
02	20606	1	0	0	0	0	0	0	0	0	0	1	-43	0	0	0	0	0	0	0	0	0	0	0	0	0	-43	0
02	20610	3	79	0	0	0	0	0	0	0	0	0	164	0	0	0	0	0	0	0	0	0	0	0	0	0	243	0
02	20733	4	0	0	0	0	0	0	0	0	0	0	164	0	0	0	0	0	0	0	0	0	0	0	0	0	164	0
02	20734	2	0	30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	30
02	20736	1	14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	14	0
02	20751	2	0	0	0	-37	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-37
02	20762	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	38	0	0	0	0	0	0	0	0	0	38	0
02	20763	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
02	20811	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
02	20812	1	10	0	0	0	0	0	0	0	0	0	30	26	0	0	0	0	0	0	0	0	15	0	0	0	55	26

Table D-1 (continued)

District	Contract Number	Number of SAs	Changed Conditions Work Orders		Plans Modifications Work Orders		Specifications Modifications Work Orders		Value Engineering Work Orders		Partnering Work Orders		City Action/Inaction Work Orders		Minor Changes Work Orders		Defective Materials Work Orders		Weather Related Damage Work Orders		Claims Work Orders		Utility Delays Work Orders		Invalid Reason Codes Work Orders		Totals Work Orders	
			Time Ext Days	SA Days	Time Ext Days	SA Days	Time Ext Days	SA Days	Time Ext Days	SA Days	Time Ext Days	SA Days	Time Ext Days	SA Days	Time Ext Days	SA Days	Time Ext Days	SA Days	Time Ext Days	SA Days	Time Ext Days	SA Days	Time Ext Days	SA Days	Time Ext Days	SA Days	Time Ext Days	SA Days
02	20831	3	0	0	0	0	0	0	0	0	0	0	5	44	0	0	0	0	0	0	0	0	0	0	0	0	5	44
02	20834	2	30	0	0	0	0	0	0	0	0	0	30	0	0	0	0	0	0	0	0	0	0	0	0	0	60	0
02	20839	2	4	58	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	58
02	20866	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
02	20867	2	0	0	0	3	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	5
02	20868	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
02	20876	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
02	20878	3	0	1	0	0	0	0	0	0	0	0	0	42	0	0	0	0	0	0	0	0	0	0	0	0	0	47
02	20899	1	24	0	37	0	0	0	0	0	0	0	60	0	0	0	0	0	0	0	0	0	0	0	0	0	121	0
02	20937	5	0	43	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	43
02	20940	4	14	0	0	5	0	0	0	0	0	0	42	0	0	0	0	0	0	0	0	0	0	0	0	0	56	5
02	20966	2	0	0	0	0	0	0	0	0	0	0	60	0	0	0	0	0	0	0	0	0	0	0	0	0	60	0
02	20975	3	39	0	0	14	0	0	0	0	0	0	0	60	0	0	0	0	0	0	0	0	0	0	0	0	39	74
02	20988	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
02	21006	2	0	0	20	12	0	0	0	0	0	0	0	15	0	0	0	0	0	0	0	0	0	0	0	0	20	27
02	21008	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
02	21009	3	0	0	0	0	0	0	0	0	0	0	7	69	0	0	0	0	0	0	0	0	0	0	0	0	7	69
02	21018	2	40	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	40	0
02	21029	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
02	21035	1	0	0	0	0	0	0	0	-20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-20
02	21052	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
02	21071	2	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	-1
02	21074	0	0	0	0	0	0	0	0	0	0	0	74	0	0	0	0	0	0	0	0	0	0	0	0	0	74	0
02	21076	5	14	14	0	0	0	0	0	0	0	0	0	-10	0	0	0	0	0	0	0	0	0	0	0	0	14	4
02	21118	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
02	21147	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3
02	21149	1	0	0	0	0	0	0	0	0	0	0	0	-8	0	0	0	0	0	0	0	0	0	0	0	0	0	-8
02	21170	2	26	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	26	0
02	21181	0	4	2	0	11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	13

Table D-1 (continued)

District	Contract Number	Number of SAs	Changed Conditions Work Orders		Plans Modification Work Orders		Specification Modification Work Orders		Value Engineering Work Orders		Partnering Work Orders		CEI Action/Inaction Work Orders		Minor Changes Work Orders		Defective Materials Work Orders		Weather Related Damage Work Orders		Claims Work Orders		Utility Delays Work Orders		Invalid Reason Codes Work Orders		Totals Work Orders	
			Time Ext Days	SA Days	Time Ext Days	SA Days	Time Ext Days	SA Days	Time Ext Days	SA Days	Time Ext Days	SA Days	Time Ext Days	SA Days	Time Ext Days	SA Days	Time Ext Days	SA Days	Time Ext Days	SA Days	Time Ext Days	SA Days	Time Ext Days	SA Days	Time Ext Days	SA Days	Time Ext Days	SA Days
02	21103	1	0	0	0	0	0	0	0	0	0	0	0	38	0	0	0	0	0	0	0	0	0	0	0	0	0	38
02	21284	1	0	0	0	0	0	0	0	0	0	0	0	15	0	0	0	0	0	0	0	0	0	0	0	0	0	15
02	[illegible]	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1
District 2 Totals			360	664	340	400	0	45	0	-20	9	0	465	632	0	0	38	0	0	0	0	0	18	0	78	8	1344	1834
03	19418	10	0	52	0	16	0	0	0	0	0	0	0	0	0	33	0	0	0	0	0	0	0	0	0	0	0	101
03	19237	11	0	90	0	45	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	55	0	55	135
03	19622	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
03	19408	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
03	19623	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
03	19708	8	0	101	31	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	31	101
03	19760	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
03	19847	6	0	0	34	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	34	0
03	19850	3	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	0
03	19950	5	32	0	3	20	0	0	0	-2	0	0	0	10	0	0	0	0	0	0	0	0	0	0	0	0	35	28
03	19986	2	3	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	30	0	0	0	35	0
03	20124	12	0	5	0	24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	29
03	20158	1	0	0	0	0	0	0	0	0	0	0	6	0	0	0	0	0	0	0	0	0	0	0	0	0	6	0
03	20198	10	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0
03	20241	3	0	4	0	46	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	50
03	20302	11	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
03	20308	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
03	20310	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
03	20343	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
03	20379	4	1	0	18	13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	19	13
03	20380	2	0	0	0	20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	20
03	20406	2	2	0	0	0	0	0	0	-20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	-20
03	20461	4	0	0	0	49	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	10	0	0	0	59
03	20507	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
03	20509	5	0	1	0	42	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	43

Table D-1 (continued)

District	Contract Number	Number of SAs	Changed Conditions Work Orders		Plans Modification Work Orders		Specification Modification Work Orders		Value Engineering Work Orders		Partnering Work Orders		CFI Action/Inaction Work Orders		Minor Changes Work Orders		Defective Materials Work Orders		Weather Related Damage Work Orders		Claims Work Orders		Utility Delays Work Orders		Invalid Reason Codes Work Orders		Totals Work Orders	
			Time Ext Days	SA Days	Time Ext Days	SA Days	Time Ext Days	SA Days	Time Ext Days	SA Days	Time Ext Days	SA Days	Time Ext Days	SA Days	Time Ext Days	SA Days	Time Ext Days	SA Days	Time Ext Days	SA Days	Time Ext Days	SA Days	Time Ext Days	SA Days	Time Ext Days	SA Days	Time Ext Days	SA Days
03	20590	4	60	-4	0	50	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	63	46
03	20594	1	0	0	59	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	59	0
03	20595	8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
03	20597	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
03	20643	1	0	0	177	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	177	0
03	20676	2	61	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	63	0
03	20703	0	0	0	0	0	0	0	0	0	0	0	0	0	12	0	0	0	0	0	0	0	0	0	0	0	12	0
03	20739	1	0	0	0	7	0	0	0	0	0	0	7	0	0	0	0	0	0	0	0	0	0	0	0	0	7	7
03	20842	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
03	20874	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	39	0	0	0	0	0	39	2
03	20904	2	0	0	0	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6
03	20942	1	7	0	2	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9	2
03	20981	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
03	20983	2	0	0	0	0	0	0	0	0	0	0	8	0	0	0	0	0	0	0	0	0	0	0	0	0	8	0
03	20984	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
03	20985	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
03	20987	0	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	0
03	21001	0	7	0	16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	23	0
03	21004	0	5	0	0	0	0	0	0	0	0	0	15	0	0	0	0	0	0	0	0	0	0	0	0	0	20	0
03	21031	1	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	0
03	21032	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
03	21067	5	10	0	0	22	0	0	0	0	0	0	0	5	0	0	0	0	0	0	0	0	0	0	0	0	10	27
03	21082	2	0	0	0	15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	15
03	21084	1	0	0	0	0	0	0	0	-25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-25
03	21086	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
03	21100	0	0	0	21	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	21	0
03	21127	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
03	21174	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
03	21203	1	0	14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	14

Table D-1 (continued)

District	Contract Number	Number of SAs	Changed Conditions Work Orders		Plans Modifications Work Orders		Specification Modifications Work Orders		Value Engineering Work Orders		Partnering Work Orders		CEI Action/InAction Work Orders		Minor Changes Work Orders		Defective Materials Work Orders		Weather Related Damage Work Orders		Claims Work Orders		Utility Delays Work Orders		Invalid Reason Codes Work Orders		Totals Work Orders	
			Time Ext Days	SA Days	Time Ext Days	SA Days	Time Ext Days	SA Days	Time Ext Days	SA Days	Time Ext Days	SA Days	Time Ext Days	SA Days	Time Ext Days	SA Days	Time Ext Days	SA Days	Time Ext Days	SA Days	Time Ext Days	SA Days	Time Ext Days	SA Days	Time Ext Days	SA Days	Time Ext Days	SA Days
District 4 Totals			201	276	353	427	0	0	0	-57	0	0	41	-3	42	33	4	0	9	10	20	4	36	40	55	0	741	786
04	19837	1	189	0	60	330	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	249	338
04	19883	5	160	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	160	0
04	19999	13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6	0	0	0	0	0	0	0	6
04	20004	15	50	0	0	94	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	40	84
04	20055	4	1	0	40	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	41	0
04	20060	18	28	72	0	21	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	28	93
04	20101	16	14	0	0	10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	14	10
04	20130	2	21	0	13	2	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	20	0	0	0	55	2
04	21207	12	39	0	18	30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	15	0	0	57	45
04	21248	17	2	2	11	106	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	13	108
04	23410	8	4	22	18	135	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	22	157
04	23402	4	0	0	15	0	0	0	0	0	0	0	0	0	0	10	0	0	0	0	0	0	0	0	0	0	15	10
04	20468	2	2	0	36	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	38	0
04	20469	3	0	0	0	125	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	125
04	20470	5	0	0	0	89	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	14	0	0	0	103
04	20498	0	0	0	10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	10	0
04	20558	1	81	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	81	0
04	20681	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
04	20743	2	0	0	1	8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	8
04	20770	2	0	0	0	30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	30
04	20783	0	12	1	48	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	60	2
04	20784	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
04	20785	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
04	0788	2	9	4	2	40	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	11	44
04	20846	4	0	30	0	0	0	0	0	0	0	0	0	8	0	0	0	0	0	0	0	0	0	0	0	0	10	30
04	0847	8	0	37	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	32
04	20950	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	10
04	24878	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table D-1 (continued)

District	Contract Number	Number of SAs	Changed Conditions Work Orders		Plans Modification Work Orders		Specification Modification Work Orders		Value Engineering Work Orders		Footnoting Work Orders		CEI Action/Inaction Work Orders		Minor Changes Work Orders		Defective Materials Work Orders		Weather Related Damage Work Orders		Claims Work Orders		Utility Delays Work Orders		Invalid Reason Codes Work Orders		Totals Work Orders	
			Time Ext Days	SA Days	Time Ext Days	SA Days	Time Ext Days	SA Days	Time Ext Days	SA Days	Time Ext Days	SA Days	Time Ext Days	SA Days	Time Ext Days	SA Days	Time Ext Days	SA Days	Time Ext Days	SA Days	Time Ext Days	SA Days	Time Ext Days	SA Days	Time Ext Days	SA Days	Time Ext Days	SA Days
04	20879	5	0	0	0	11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	11
04	20912	2	0	0	8	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	8	2
04	20947	2	43	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	7	0	0	0	54	0
04	21018	1	0	0	15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	15	0
04	21090	1	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2
04	21128	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
04	21139	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
04	21187	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
04	188	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
04	189	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
04	165		0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1
District 4 Totals			**721**	**193**	**397**	**1043**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**10**	**0**	**0**	**2**	**24**	**0**	**0**	**27**	**80**	**8**	**0**	**1097**	**1309**
05	9788	4	0	0	5	0	0	0	0	0	0	0	0	0	0	0	0	0	5	0	0	0	0	0	0	0	20	10
05	176	11	7	17	0	0	0	0	0	0	0	0	0	0	0	27	0	0	0	0	0	0	0	0	0	0	7	94
05	20005	4	0	0	12	39	0	0	0	0	0	0	0	-60	0	0	0	0	0	0	0	0	0	0	0	0	12	-30
05	20012	2	2	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	0
05	20214	13	11	76	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	11	76
05	20072	4	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	0
05	20921	7	9	0	14	0	0	0	0	30	0	0	0	0	10	0	0	0	0	0	0	0	0	0	0	0	22	30
05	20607	9	2	0	0	61	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	61
05	20612	8	0	157	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	157
05	20657	2	7	0	43	0	0	0	0	0	0	0	0	0	10	0	0	0	0	0	0	0	0	0	0	0	60	0
05	20660	14	1	0	0	10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	10
05	20741	2	0	1	12	3	0	0	0	0	0	0	13	0	0	0	0	0	0	0	0	0	0	0	0	0	25	4
05	20783	3	0	0	9	1	0	0	0	0	0	0	0	4	4	0	0	0	0	0	0	0	0	0	0	0	13	5
05	20794	1	0	0	0	0	0	0	0	0	0	0	0	17	0	27	0	0	0	0	0	0	0	0	0	0	0	44
05	20799	2	19	0	10	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	29	6
05	20854	2	0	0	20	16	0	0	0	0	0	0	0	0	0	0	0	0	0	10	0	0	0	0	0	0	20	24
05	20883	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table D-1 (continued)

District	Contract Number	Number of SAs	Changed Conditions Work Orders		Plans Modification Work Orders		Specification Modification Work Orders		Value Engineering Work Orders		Partnering Work Orders		CEI Action/Inaction Work Orders		Minor Changes Work Orders		Defective Materials Work Orders		Weather Related Damage Work Orders		Claims Work Orders		Utility Delays Work Orders		Invalid Reason Codes Work Orders		Totals Work Orders	
			Time Ext Days	SA Days	Time Ext Days	SA Days	Time Ext Days	SA Days	Time Ext Days	SA Days	Time Ext Days	SA Days	Time Ext Days	SA Days	Time Ext Days	SA Days	Time Ext Days	SA Days	Time Ext Days	SA Days	Time Ext Days	SA Days	Time Ext Days	SA Days	Time Ext Days	SA Days	Time Ext Days	SA Days
05	20883	1	10	0	0	0	0	0	0	0	0	0	0	21	0	0	0	0	0	0	0	0	0	0	0	0	10	21
05	20916	2	0	0	0	1	0	0	0	0	0	0	0	2	0	40	0	0	0	0	0	0	0	0	0	0	0	43
05	20926	0	0	3	0	5	0	0	0	0	0	0	0	14	0	0	0	0	0	0	0	0	0	0	0	0	0	22
05	20927	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
05	20981	0	21	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	21	0
05	21010	0	0	7	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	8
05	21022	0	0	12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	12
05	21041	0	6	0	0	13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6	13
05	21063	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
05	21066	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
05	21084	1	0	0	13	20	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	13	21
05	21095	1	0	0	0	0	0	0	0	0	0	0	0	15	22	0	0	0	0	0	0	0	0	0	0	0	22	15
05	21105	3	0	2	0	0	0	0	0	0	0	0	33	0	0	0	0	0	0	0	0	0	0	0	0	0	33	2
05	21120	0	0	0	30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	30	0
05	21135	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
05	21136	0	65	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	65	0
05	21160	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
05	21162	1	0	0	0	0	0	0	0	0	0	0	0	21	0	0	0	0	0	0	0	0	0	0	0	0	0	21
05	21172	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
05	21173	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
05	21193	0	0	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6
05	21194	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
05	21202	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
05	21222	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
05	21223	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
05	21240	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
05	21242	0	1	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	3	0	0	0	0	0	0	1	6
05	21262	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
05	21313	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table D-1 (continued)

District	Contract Number	Number of SAs	Changed Conditions Work Orders		Plans Modification Work Orders		Specification Modification Work Orders		Value Engineering Work Orders		Partnering Work Orders		CEI Action/Inaction Work Orders		Minor Changes Work Orders		Defective Materials Work Orders		Weather Related Damage Work Orders		Claims Work Orders		Utility Delays Work Orders		Invalid Reason Codes Work Orders		Totals Work Orders	
			Time Ext Days	SA Days	Time Ext Days	SA Days	Time Ext Days	SA Days	Time Ext Days	SA Days	Time Ext Days	SA Days	Time Ext Days	SA Days	Time Ext Days	SA Days	Time Ext Days	SA Days	Time Ext Days	SA Days	Time Ext Days	SA Days	Time Ext Days	SA Days	Time Ext Days	SA Days	Time Ext Days	SA Days
05	21338	0	0	0	0	0	0	0	0	0	0	0	0	16	0	0	0	0	0	0	0	0	0	0	0	0	0	16
05	21345	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	2	0
05	21349	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
05	21455	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
District 5 Totals			**175**	**284**	**180**	**177**	**0**	**0**	**0**	**66**	**0**	**0**	**47**	**65**	**46**	**144**	**0**	**0**	**14**	**23**	**0**	**0**	**5**	**0**	**0**	**0**	**467**	**759**
06	18831	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
06	19004	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
06	19063	21	91	0	0	68	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	91	68
06	20023	4	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	25	0	0	5	25
06	20031	2	0	115	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	24	0	0	0	139
06	21336	3	20	0	0	0	0	0	0	-60	0	0	0	0	0	0	0	0	8	0	0	0	0	0	0	0	28	-60
06	20062	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
06	20747	4	10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	10	0
06	20823	3	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
06	20880	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
06	20910	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
06	20920	1	11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	11	0
06	20921	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
06	20932	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
06	20933	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
06	20957	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
06	21062	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
06	21063	3	0	0	0	0	0	0	0	0	0	0	31	0	0	0	0	0	5	0	0	0	0	0	0	0	45	0
06	21096	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
06	21097	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
06	21131	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
06	21190	1	0	0	0	0	0	0	0	-61	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-61
06	21197	2	16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	16	0
06	21272	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table D-1 (continued)

District	Contract Number	Number of SAs	Changed Conditions Work Orders		Plans Modifications Work Orders		Specification Modification Work Orders		Value Engineering Work Orders		Partnering Work Orders		CLI Action/Inaction Work Orders		Minor Changes Work Orders		Defective Materials Work Orders		Weather Related Damage Work Orders		Claims Work Orders		Utility Delays Work Orders		Legal & Reason Codes Work Orders		Totals Work Orders	
			Time Ext Days	SA Days	Time Ext Days	SA Days	Time Ext Days	SA Days	Time Ext Days	SA Days	Time Ext Days	SA Days	Time Ext Days	SA Days	Time Ext Days	SA Days	Time Ext Days	SA Days	Time Ext Days	SA Days	Time Ext Days	SA Days	Time Ext Days	SA Days	Time Ext Days	SA Days	Time Ext Days	SA Days
District 07 Totals			**463**	**135**	**10**	**68**	**0**	**0**	**0**	**121**	**0**	**0**	**31**	**9**	**0**	**0**	**0**	**0**	**13**	**0**	**0**	**0**	**0**	**40**	**0**	**0**	**517**	**447**
07	9535	19	0	5	0	17	0	0	0	0	0	0	32	7	0	0	0	0	0	0	0	0	0	2	0	0	32	6
07	9125	35	0	172	0	608	0	0	0	0	0	0	0	17	0	0	0	0	0	0	0	0	0	0	0	0	0	772
07	9599	9	100	0	0	-6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	100	-6
07	19431	9	35	7	19	0	0	0	0	0	0	0	0	0	14	0	0	0	0	0	0	0	0	0	0	0	68	7
07	9972	10	131	4	0	0	0	0	0	0	0	0	93	0	0	0	0	0	0	0	0	0	0	0	0	0	224	4
07	19947	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
07	20183	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
07	20287	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0
07	20393	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
07	20486	2	0	0	35	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	44	0
07	20530	13	20	2	0	26	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	72	60	0	0	109	42
07	20572	4	0	31	0	7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	38
07	20621	4	40	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	40	0
07	20693	2	0	0	38	0	0	0	0	0	0	0	14	0	0	0	0	0	0	0	0	0	0	0	0	0	52	0
07	20775	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
07	20806	1	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6	0
07	20821	14	163	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	77	0	0	163	77
07	20856	1	45	0	0	68	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	11	19	0	0	56	87
07	20858	2	0	0	0	79	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	79
07	20859	0	47	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	47	0
07	20905	2	0	0	0	15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	15
07	20997	1	0	34	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	34
07	21021	0	0	0	0	0	0	0	0	0	0	0	28	0	0	0	0	0	0	0	0	0	0	0	0	0	28	0
07	21200	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
07	21220	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
07	21311	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
07	21341	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
07	21342	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table D-1 (continued)

District	Contract Number	Number of SAs	Changed Conditions Work Orders		Plans Modifications Work Orders		Specifications Modifications Work Orders		Value Engineering Work Orders		Partnering Work Orders		C&I Action/Inaction Work Orders		Minor Changes Work Orders		Defective Materials Work Orders		Weather Related Damage Work Orders		Claims Work Orders		Utility Delays Work Orders		Invalid Reason Codes Work Orders		Totals Work Orders	
			Time Ext Days	SA Days	Time Ext Days	SA Days	Time Ext Days	SA Days	Time Ext Days	SA Days	Time Ext Days	SA Days	Time Ext Days	SA Days	Time Ext Days	SA Days	Time Ext Days	SA Days	Time Ext Days	SA Days	Time Ext Days	SA Days	Time Ext Days	SA Days	Time Ext Days	SA Days	Time Ext Days	SA Days
District 7 Totals			**604**	**231**	**96**	**864**	**0**	**0**	**0**	**0**	**0**	**0**	**107**	**24**	**14**	**0**	**0**	**0**	**5**	**6**	**0**	**0**	**85**	**168**	**0**	**0**	**963**	**1217**
08	9760	16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	40	0	234	0	0	0	0	2	274
08	9720	18	3	337	0	2	0	0	0	0	0	0	0	0	0	0	0	0	2	34	0	0	0	0	0	0	5	373
08	19832	10	0	276	0	103	0	0	0	0	0	0	51	0	0	0	0	0	2	0	0	0	0	0	0	0	53	381
08	19860	21	0	177	0	27	0	0	0	0	0	0	0	55	0	0	0	0	2	34	0	0	0	0	0	0	2	209
08	20002	13	0	122	0	90	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	212
08	20185	16	48	116	0	0	0	0	0	0	0	0	110	0	0	0	0	0	0	0	0	0	0	0	0	0	107	116
08	20322	4	110	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	110	0
08	20620	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
08	31865	1	3	0	42	0	0	0	0	0	0	0	28	45	28	0	0	0	0	1	0	0	0	0	0	0	112	45
08	18267	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
District 8 Totals			**171**	**1026**	**42**	**74**	**0**	**0**	**0**	**0**	**0**	**0**	**208**	**95**	**28**	**0**	**0**	**0**	**0**	**108**	**0**	**234**	**0**	**0**	**0**	**0**	**457**	**1307**

APPENDIX E
INNOVATIVE CONTRACTING TECHNIQUES

Table E-1 Innovative contracting techniques

District	Contract Number	Number of SAs	Original Contract Days	Present Contract Days	Days Used	Unused Days	Difference Or'ginal Present	% of Increase / Decrease	Time Extension	SA Days	Weather Days	Totals Work Orders		Code	Innovative Contract Type
												Time Ext Days	SA Days		
02	20431	1	300	316	316	0	16	5%	19	-3	22	-3	-3	B0	LUMP SUM
02	20966	2	90	150	150	0	60	67%	60	0	0	60	0	B0	LUMP SUM
02	20975	3	120	238	238	0	118	98%	44	74	5	39	74	B0	LUMP SUM
02	20988	1	150	150	119	31	0	0%	0	0	0	0	0	B0	LUMP SUM
02	21008	1	180	194	176	18	14	8%	14	0	14	0	0	B0	LUMP SUM
02	21018	3	150	251	251	0	101	67%	56	45	25	7	69	B0	LUMP SUM
02	21028	2	150	203	203	0	53	35%	53	0	13	40	0	B0	LUMP SUM
02	20866	1	90	91	78	13	1	1%	1	0	1	0	0	B0	LUMP SUM
02	20867	2	207	258	270	12	51	25%	46	5	46	0	5	B0	LUMP SUM
02	21052	2	180	193	172	21	13	7%	13	0	13	0	0	B0	LUMP SUM
02	21071	2	150	164	164	0	14	9%	36	22	18	0	-4	B0	LUMP SUM
02	21076	5	180	216	216	0	36	20%	36	0	18	14	4	B0	LUMP SUM
02	21118	0	30	30	16	14	0	0%	0	0	0	0	0	B0	LUMP SUM
02	21147	3	210	216	199	17	6	3%	6	0	6	0	0	B0	LUMP SUM
02	21149	1	45	40	40	0	-5	-11%	3	-8	3	0	-8	B0	LUMP SUM
02	21179	2	150	212	130	82	62	41%	62	0	76	36	0	B0	LUMP SUM
02	21181	0	60	94	94	8	34	57%	34	0	17	4	13	B0	LUMP SUM
02	21183	1	60	22	22	8	-38	-63%	0	38	0	0	38	B0	LUMP SUM
02	21284	1	90	75	75	0	15	-17%	0	-15	0	0	15	B0	LUMP SUM
02	21285	0	45	52	50	2	7	16%	7	0	4	0	3	B0	LUMP SUM
03	20942	1	100	136	139	3	36	36%	34	2	25	9	2	B0	LUMP SUM
01	21141	2	150	163	110	53	13	9%	13	0	13	0	0	B0	LUMP SUM
01	21177	1	115	121	120	1	6	5%	10	-4	10	0	-4	B0	LUMP SUM

Table E-1 (continued)

District	Contract Number	Number of SAs	Original Contract Days	Present Contract Days	Days Used	Unused Days	Difference Original Present	% of Increase / Decrease	Time Extension	SA Days	Weather Days	Totals Work Orders Time Ext Days	Totals Work Orders SA Days	Code	Innovative Contract Type
01	21021	0	50	72	69	3	22	44%	22	0	22	0	0	B0	LUMP SUM
01	21321	0	40	40	35	5	0	0%	0	0	0	0	0	B0	LUMP SUM
01	21344	0	30	32	31	1	2	7%	2	0	2	0	0	B0	LUMP SUM
07	20858	2	50	133	133	0	83	166%	4	79	4	0	79	B0	LUMP SUM
07	20997	1	69	129	127	2	60	87%	26	34	26	0	34	B0	LUMP SUM
07	21220	1	45	52	49	3	7	16%	7	0	7	0	0	B0	LUMP SUM
07	21311	1	10	10	9	1	0	0%	0	0	0	0	0	B0	LUMP SUM
07	21341	0	45	54	54	0	9	20%	9	0	9	0	0	B0	LUMP SUM
05	21066	0	40	40	39	1	0	0%	0	0	0	0	0	B0	LUMP SUM
05	21172	0	70	70	68	2	0	0%	0	0	0	0	0	B0	LUMP SUM
05	21222	0	60	70	68	2	10	17%	10	0	10	0	0	B0	LUMP SUM
05	21345	0	30	34	34	0	4	13%	4	0	1	3	0	B0	LUMP SUM
05	21435	0	25	25	24	1	0	0%	0	0	0	0	0	B0	LUMP SUM
04	20410	8	310	513	513	0	203	65%	36	167	14	22	167	B1	BONUS
04	20467	4	420	455	344	111	35	8%	25	10	10	15	10	B1	BONUS
04	20681	0	220	220	186	34	0	0%	0	0	0	0	0	B1	BONUS
04	20878	3	340	354	304	50	14	4%	14	0	14	0	0	B1	BONUS
05	20214	13	855	977	977	0	122	14%	46	76	35	11	76	B1	BONUS
04	19999	13	975	1012	852	160	37	4%	31	6	31	0	6	B1	BONUS
07	19826	5	676	714	714	0	38	6%	38	0	38	0	0	B1	BONUS
06	20390	3	745	718	712	6	-27	-4%	33	-60	5	28	-60	B1	BONUS
06	20602	8	600	611	593	18	11	2%	11	0	11	0	0	B1	BONUS
06	20933	1	100	103	89	14	3	3%	3	0	3	0	0	B1	BONUS

Table E.1 (continued)

District	Contract Number	Number of SAs	Original Contract Days	Present Contract Days	Days Used	Unused Days	Difference Original - Present	% of Increase / Decrease	Time Extension	SA Days	Weather Days	Totals Work Orders		Code	Innovative Contract Type
												Time Ext Days	SA Days		
06	20957	0	400	408	299	109	8	2%	8	0	8	0	0	B1	BONUS
06	21062	2	280	295	268	27	15	5%	15	0	15	0	0	B1	BONUS
06	21096	1	250	282	230	52	32	13%	32	0	32	0	0	B1	BONUS
06	21097	1	280	296	257	39	16	6%	16	0	16	0	0	B1	BONUS
06	21196	1	270	214	179	35	-56	-21%	5	-61	5	0	-61	B1	BONUS
01	20863	2	120	86	85	1	-34	-28%	7	-41	7	0	-41	B1	BONUS
01	20471	0	100	100	75	25	0	0%	0	0	0	0	0	B1	BONUS
01	21004	0	110	110	40	70	0	0%	0	0	0	0	0	B1	BONUS
02	20733	4	500	354	354	0	-146	-29%	18	0	18	-164	0	B2	A + B BIDDING
02	20868	3	360	360	291	69	0	0%	0	0	0	0	0	B2	A + B BIDDING
02	20419	1	270	413	411	2	143	53%	143	0	22	121	0	B2	A + B BIDDING
02	20811	6	500	500	478	22	0	0%	0	0	0	0	0	B2	A + B BIDDING
02	20831	3	240	321	313	8	81	34%	61	20	32	5	44	B2	A + B BIDDING
02	20834	2	120	207	204	3	87	73%	87	0	27	60	0	B2	A + B BIDDING
02	20940	4	290	472	468	4	182	63%	177	5	121	56	5	B2	A + B BIDDING
02	21029	5	166	166	131	35	0	0%	0	0	0	0	0	B2	A + B BIDDING
02	21090	1	120	104	101	3	-16	-13%	4	-20	4	0	-20	B2	A + B BIDDING
03	20302	11	690	705	665	40	15	2%	14	1	14	0	1	B2	A + B BIDDING
04	20248	17	576	849	845	4	273	47%	83	190	80	14	190	B2	A + B BIDDING
05	20657	3	249	332	473	-141	83	33%	83	0	23	60	0	B2	A + B BIDDING
06	20919	9	214	235	201	34	21	10%	21	0	20	1	0	B2	A + B BIDDING
06	10861	4	550	610	610	0	60	11%	60	0	60	0	0	B3	LANE RENTAL
06	20747	4	180	237	237	0	57	32%	57	0	38	19	0	B3	LANE RENTAL

Table E-1 (continued)

District	Contract Number	Number of SAs	Original Contract Days	Present Contract Days	Days Used	Unused Days	Difference Original-Present	% of Increase / Decrease	Time Extension	SA Days	Weather Days	Totals Work Orders		Code	Innovative Contract Type
												Time Ext Days	SA Days		
07	20287	[illegible]	600	621	495	126	21	4%	15	6	14	1	6	B5	INCENTIVE/DISINCENTIVE
05	20883	2	430	461	369	92	31	7%	31	0	31	0	0	B5	INCENTIVE/DISINCENTIVE
01	19529	13	505	573	572	1	68	13%	41	27	39	2	27	B5	INCENTIVE/DISINCENTIVE
01	19817	56	635	1156	1166	10	521	82%	95	426	41	54	426	B5	INCENTIVE/DISINCENTIVE
01	20228	12	590	510	518	8	-80	14%	61	141	61	0	141	B5	INCENTIVE/DISINCENTIVE
01	20775	10	400	325	330	5	75	19%	0	75	0	0	75	B5	INCENTIVE/DISINCENTIVE
01	21026	1	145	150	150	0	5	3%	11	-6	11	0	-6	B5	INCENTIVE/DISINCENTIVE
03	20589	5	320	395	386	9	75	23%	32	43	32	0	43	B5	INCENTIVE/DISINCENTIVE
04	20860	12	510	667	667	0	157	31%	64	93	36	28	93	B5	INCENTIVE/DISINCENTIVE
04	20783	9	220	294	293	1	74	34%	67	7	7	60	7	B5	INCENTIVE/DISINCENTIVE
04	20846	4	272	325	324	1	53	19%	23	30	13	10	30	B5	INCENTIVE/DISINCENTIVE
05	20607	[illegible]	300	380	380	0	80	27%	19	61	17	2	61	B5	INCENTIVE/DISINCENTIVE
05	20744	3	400	469	460	9	69	17%	69	0	40	25	4	B6	LIQUIDATED SAVINGS
05	21100	3	145	201	201	0	56	39%	56	0	21	33	2	B6	LIQUIDATED SAVINGS
05	21135	0	130	210	210	0	80	62%	80	0	80	0	0	B6	LIQUIDATED SAVINGS
06	19831	3	500	535	400	135	35	7%	35	0	35	0	0	B6	LIQUIDATED SAVINGS
06	21063	3	200	263	135	128	63	32%	63	0	18	45	0	B6	LIQUIDATED SAVINGS
02	20937	5	390	483	386	97	93	24%	66	27	50	0	43	B6	LIQUIDATED SAVINGS
02	20734	2	180	154	138	16	26	14%	4	30	4	0	30	B6	LIQUIDATED SAVINGS
02	20839	2	210	351	327	24	141	67%	85	56	79	4	58	B6	LIQUIDATED SAVINGS
07	20693	2	400	453	435	18	53	13%	53	0	1	52	0	B8	DESIGN/BUILD (MAJOR)
03	20124	12	785	956	948	8	171	22%	142	29	142	0	29	B9	WARRANTY

APPENDIX F
FUZZY INFERENCE

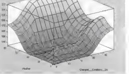

Figure F-1 Weather – changed conditions (SA) inference for short term projects

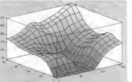

Figure F-2 Weather – plans modification (SA) inference for short term projects

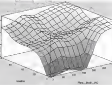

Figure F-3 Weather – plans modifications (WO) inference for short term projects

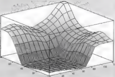

Figure F-4 Weather – CEI (WO) inference for short term projects

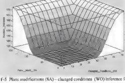

Figure F-5 Plans modifications (SA) – changed conditions (WO) inference for short term projects

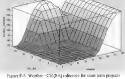

Figure F-6 Weather – CEI(SA) inference for short term projects

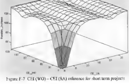

Figure F-7 CEI (WO) – CEI (SA) inference for short term projects

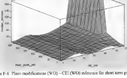

Figure F-8 Plans modifications (WO) – CEI (WO) inference for short term projects

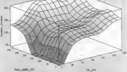

Figure F-9 Plans modifications (WO) – CEI (WO) inference for short term projects

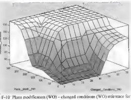

Figure F-10 Plans modification (WO) – changed conditions (WO) inference for short term projects

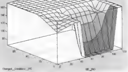

Figure F-11 Changed conditions (WO) – CEI (WO) inference for short term projects

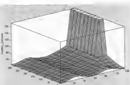

Figure F-12 Plans modifications (WO) CEI (WO) inference for short term projects

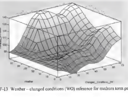

Figure F-13 Weather – changed conditions (WO) inference for medium term projects

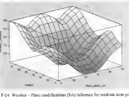

Figure F-14 Weather – Plans modifications (SA) inference for medium term projects

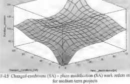

Figure F-15 Changed conditions (SA) – plans modification (SA) work orders inference for medium term projects

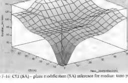

Figure F-16 CEI (SA) – plans modification (SA) inference for medium term projects

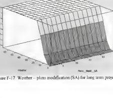

Figure F-17 Weather – plans modification (SA) for long term projects

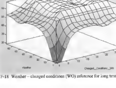

Figure F-18 Weather – changed conditions (WO) inference for long term projects

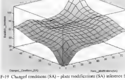

Figure F-19 Changed conditions (SA) – plans modifications (SA) inference for long term projects

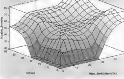

Figure F-20 CEI (SA) – Plans modification (SA) inference for long term projects

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